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Analysis of Electrification Infrastructure Options and the Cost Implications in the Railway Industry

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SOMMARIO

Il progetto di estensione del sistema elettrico della rete ferrioviaria inglese presenta numerose sfide, specialmente nel caso di quegli *overbridges* per i quali la prevista distanza tra i cavi di alimentazione dell'*Overhead Line* Equipment e il soffitto risulta inadeguata a rispettare gli standards Europei per '*electrical clearances'.* Differenti opzioni per modifiche infrastrutturali sono disponibili ma il processo decisionale risulta penalizzato dalla limitata ricerca riguardante strumenti e metodologie *multi-asset*. Lo scopo di questa tesi e' pertanto sviluppare un *Whole Life Cycle cost model* per valutare l'alternativa infrastrutturale piu' conveniente, riferendo i costi al comportamento dei principali *assets* lungo l'orizzonte di pianificazione stabilito. Un apposito programma Excel e' stato inoltre creato per automatizzare i calcoli e facilitare le decisioni, attraverso la rappresentazione dei costi totali mediante un pratico istogramma, nel quale adf ogni opzione corrisponde a una barra.

ABSTRACT

The programme of the extension of Britain's railway electrification presents several challenges, especially for those overbridges where the expected gap between the Overhead Line Equipment power cables and the ceiling results inadequate to comply with the European standards for electrical clearances. Options for infrastructural modifications are available by the decision-making process is penalised by a limited research on multi-asset methodologies. This thesis aims therefore at developing a Whole Life Cycle cost model to assess the best option for infrastructure alterations, by linking the costs to the behaviour of the principal assets over the planning horizon. An Excel-based software tool has been developed, which accounts for the behaviours of tracks, overbridges and Overhead Line Equipment and displays the total costs for each option by means of a practical histogram.

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LIST OF ABBREVIATIONS

CAPEX	Capital Expenditure
CER	Cost Estimating Relationship
CP	Control Period
EPSRC	Engineering and Physical Sciences Research Council
GRIP	Governance for Railway Investment Projects
kV	Kilovolt
MGT	Million Gross Tons
MS	Microsoft
NPV	Net Present Value
OLE	Overhead Line Equipment
OPEX	Operational Expenditures
ORR	Office of Rail and Road
PPM	Public Performance Measure
RAMS	Reliability, Availability, Maintainability and Safety
STK	Single Track Kilometre
TOC	Train Operating Company
TPV	Total Present Value
UK	United Kingdom
VBA	Visual Basic for Application
WLC	Whole Life Cycle

1 INTRODUCTION

1.1 Research background

The railway industry is experiencing a period of radical changes and indisputable growth worldwide. The United Kingdom is facing the challenge with the extension of the electrification system to the network, because electrified routes provide not only 'faster, quieter and more reliable journeys' for passengers and freight transportation, but also a reduction of up to 35% in carbon emissions (Network Rail, 2015b). The selected system is the Overhead Line Equipment (OLE), which supplies the electric power to trains by means of contact wires kept suspended over the track. However, the overall electrification project includes also considerable civil modifications to railway assets, especially in proximity of overbridges.

In the railway system, three different types of asset can be referred to as 'bridge':

- Overbridges: "the purpose of an overbridge is to carry another service (such as roadways, footways and public utilities) over the railway" (Network Rail, 2010)
- Underbridges: "the purpose of an underbridge is to carry rail traffic across a geographic feature or obstruction such as a road, river, valley, estuary and railway." (Network Rail, 2010)
- Tunnels: "the purpose of a tunnel is to allow the passage of services through or under a land feature such as high topographic relief, or a river, where the formation of alternative structures such as cuttings or bridges would have been undesirable on economic or technical grounds" (Network Rail, 2010)

For many railway overbridges, the expected gap between power cables and the ceiling results inadequate to comply with the European standards for electrical clearances, so that major alterations are required on the railway infrastructure. While bridge reconstruction and track lowering allow for the 'enhanced' level of electrical clearances, a third option is characterised by 'reduced' standard levels and no major structural changes to the infrastructure. The best infrastructure option is represented by the most effective compromise between initial costs and maintenance costs, considering all the assets involved. An illustration of the electrical clearances challenge is provided in Figure 1-1.

Because of long service life span of assets and considerable capital investments required in any railway project, a WLC cost model emerges as the most appropriate methodology since “it is a process of assessing the costs of a product throughout its different life-cycle phases, contributing to a more conscious decision-making process” (Andrade, 2008).

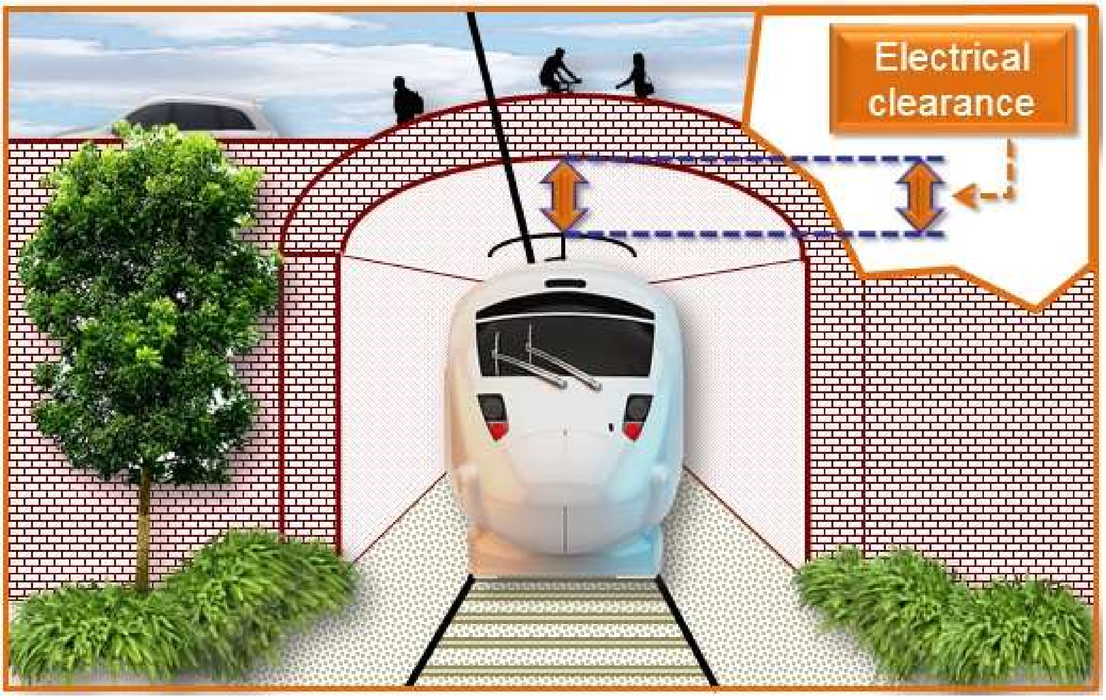

Figure 1-1 Representation of electrical clearances

1.2 Research Motivation

The installation of the electrical system to overbridges is a requisite for the complete electrification of rail routes. Companies within the industry have provided many solutions to fit the Overhead Line Equipment to overbridges and comply at the same time with the standard levels for electrical clearances. However, the decision-making process, while looking towards the best compromise between capital investments and maintenance costs occurring over a defined period of time, can rely on limited research on multi-asset methodologies. In addition, since many overbridges belong to the Victorian architecture legacy buildings and are protected by the Government, the industry is interested in assessing other options beyond bridge demolition and reconstruction. These considerations suggest there is a need to investigate and compare the available infrastructure options from a cost-benefit perspective, through the use of a cost model that considers the implications and the behaviour of the major assets involved by modifications.

1.3 The AUTONOM Project

The AUTONOM Project is a significant research-based project started in March 2013 at Cranfield University and has been sponsored by the EPRSC and more than ten industrial partners across different industries. Its vision is to enhance the combination among architectural layers in data-rich backgrounds; in particular, the aim is to provide tools and frameworks for assessing advantages and costs of integrated condition-based maintenance strategies. The project is structured in four work packages: Integration, Data fusion and mobile platforms, Planning and scheduling based on intelligent and reconfigurable business processes, and Cost analysis (the package this thesis belongs to).

1.4 Scope

It has been required that the project focuses on overbridges rather than underbridges nor tunnels, while the assets considered in the cost model are tracks, OLE and overbridges. The model evaluates the best option among bridge reconstruction, track lowering and reduced level of clearances, while the model does not assess alternatives options found in the Literature.

1.5 Aim and Objectives

The aim of the project is to develop a Whole Life Cycle cost model to evaluate the available infrastructure options to extend the electrical system to overbridges.

To achieve the aim, the objectives that have been defined are to:

- Conduct a comprehensive Literature Review on Whole Life Cycle cost modelling and railway maintenance
- Capture current practices in Whole Life Cycle cost modelling
- Analyse technically the available options for infrastructure alterations
- Identify Whole Life Cycle cost drivers and define Cost Estimating Relationships
- Validate the research results through experts' opinions

1.6 Collaborator Company

The Collaborator Company has a key expertise in the railway sector and has provided a set of data to analyse. The most relevant strategic change since its foundation has been to bring all maintenance activities back in house to establish a standardised way of working across the different areas. This achievement has been the result of a big investment policy of empowerment and enhancement of employees' capabilities, together with continuous collaborations with the rest of the industry and academic institutions as well.

1.7 Thesis Structure

The structure of the thesis consists of seven chapters, which are represented in Figure 1-2. Chapter 2 is related to information and findings from the literature and covers many topics of the railway industry. Some case studies from past electrification programmes are also discussed. Chapter 3 is dedicated to the description of the methodology followed throughout the project. In chapter 4 the model development is presented, starting from the requirements set by the stakeholders and proceeding with the options description and data analysis, ending with cost equations and asset degradation models. In chapter 5 the tool structure is presented as well as the process followed for the research validation. Chapter 6 contains the critical evaluation of the whole project, highlighting strengths and weaknesses of the cost model and tool as. Chapter 7 concludes the present report with recommendations for further works.

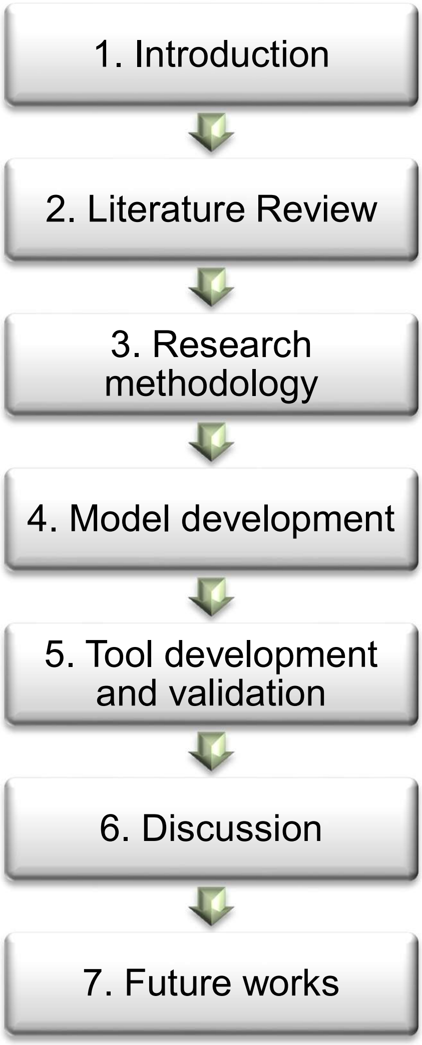

Figure 1-2 Thesis structure

1.8 Summary

This chapter represents the conceptual aspects of the thesis. After providing the context of the research, the project stakeholders have been described, together with the research motivation, in order to understand the importance and the novelty brought by the present work. Then, aims and objectives have been presented, together with the definition of what is considered in scope. The chapter ends with the description of the structure of the thesis.

2 LITERATURE REVIEW

2.1 Introduction

This thesis aims at developing a WLC cost model to assess the best infrastructure option to fit the electrification system to overbridges. First, it is required to clarify what WLC means and which are its cost drivers. Then, an overview of railway maintenance is presented, together with the asset degradation models. Finally, an outlook of the industry is discussed, focusing on future climate changes impacting the industry. The complete list of topics discussed in this chapter is shown in Figure 2-1.

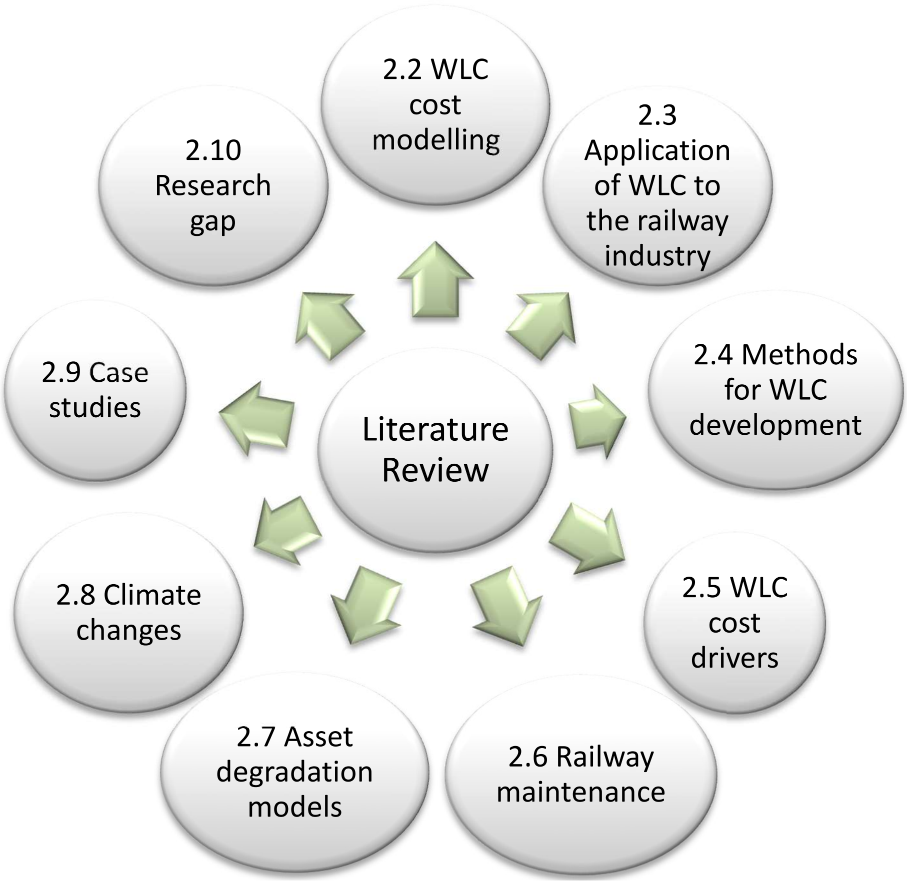

Figure 2-1 Literature Review structure

The Literature Review has been carried out after reading more than eighty documents among journal papers, conference papers, company's white papers and official websites. It covers many topics relevant for the thesis, but at the same time reveals important gaps, especially in the field of multi-asset cost modelling for the railway industry.

2.2 Whole Life Cycle cost modelling

Whole Life Cycle costing is a structured methodology that helps decision-makers in selecting the option that minimises the sum of all relevant costs occurring over the whole service life of a product, system or service (Boussabaine and Kirkham, 2004).

The concept was gradually developed during the last sixty years, as Figure 2-2 displays. Before 1960s, capital investment decisions were drawn basically on the basis of capital costs, because the general belief was that, along with increasing initial investments, decreasing long-term expenditures would be consequently experienced (Terotechnology). The concept then evolved to 'cost-in-use' with a consideration of the costs associated with also the operations of an asset. (Boussabaine and Kirkham, 2004).

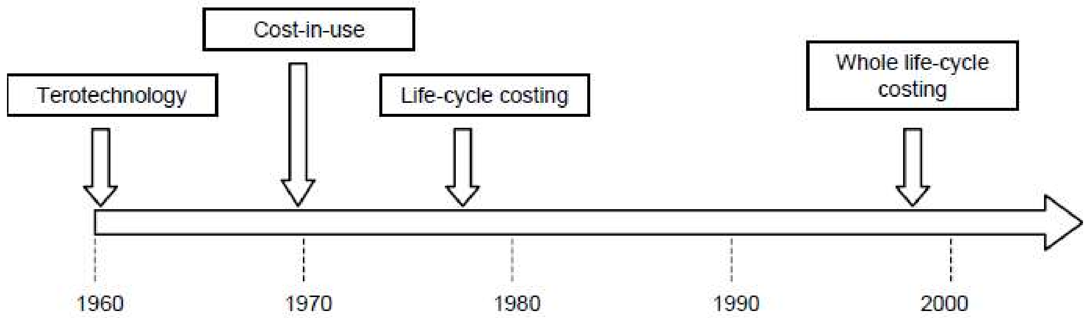

Figure 2-2 The evolution timeline of WLC costing model (Boussabaine and Kirkham, 2004)

Only in the late 1970s, analysts and accounting managers began introducing forecasting techniques for the evaluation of future costs (Life Cycle Costing) but the method was adopted only for projects with huge capital investments. Interestingly, it was nevertheless demonstrated that an ignorance of likely future costs would make companies operate in a more expensive future environment (Smith, 1999).

Towards the end of the last century, the technique evolved to 'Whole Life Costing', which differs from LCC because it considers the costs occurring over not only the economic life (the period of commercial interest) but rather over the entire life of a product or service.

Nowadays there is an ongoing debate about commonalities and differences between LCC and WLC but, according to Sarpong (2013), they should be considered not interchangeable.

WLC is a cost method that deals with future costs; therefore a cost engineering approach is required. However, no cost modelling techniques are suitable for every stage of the product/project life-cycle, since the quantity of available data and uncertainty vary over time (Trivailo et al., 2012), as explained in Figure 2-3.

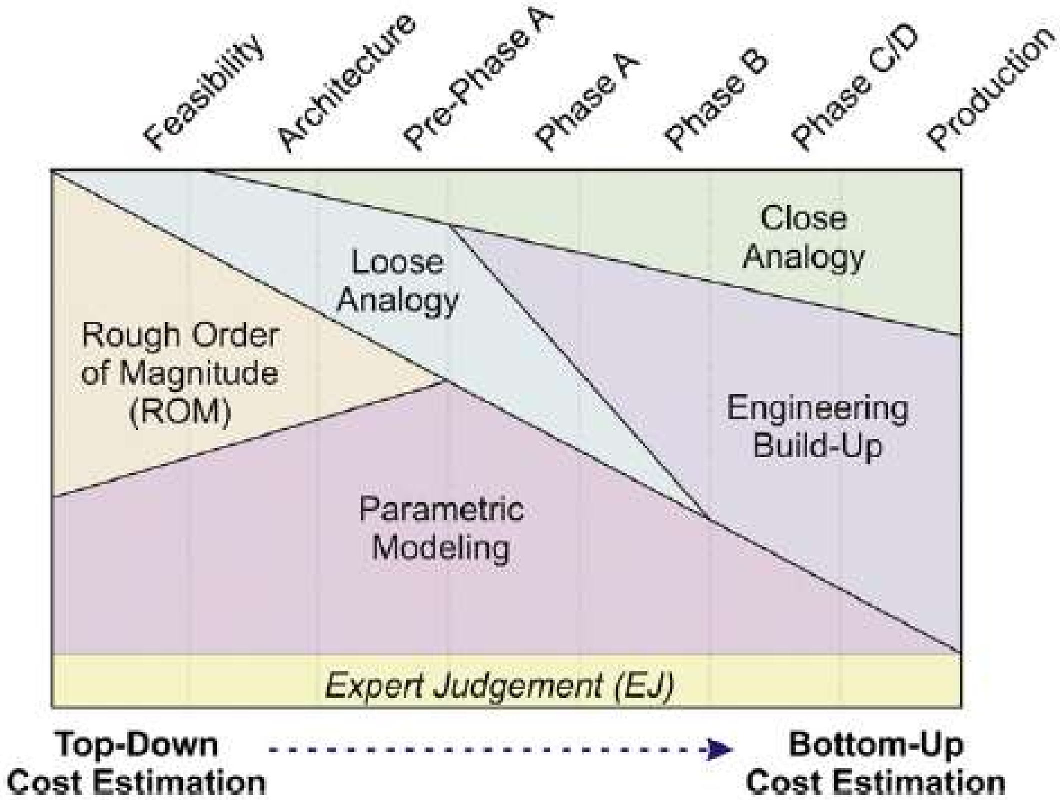

Figure 2-3 Quantitative application of Cost Estimating Methods according to project phase (Trivailo et al., 2012)

According to Ibigbari (2014), cost estimation methods can be classified in:

1. Engineering procedures ('bottom-up'): the cost of a product or service is the sum of the costs of all components or parts. Although the level of precision shall be accurate, time and effort required for the calculation may result excessive.
2. Analogy: when data are not available, analogies between different products or projects can be drawn regarding current and future costs. This approach relies mostly on experts' judgments so that a high levels of experience and competence is required.
3. Parametric ('top-down'): costs are estimated from parameters (cost drivers) that drive the costs in an identified way, characterised generally by an unsophisticated equation (Cost Estimating Relationship). Based on historical

data, its advantages range from reduced project times and easiness of use to low requirements for product information. Conversely, it may be considered simplistic and not applicable when past data are not available.

According to Ben-Arieh & Qian (2003), the list includes also intuitive methods (based only on estimators' past experience), while engineering ones are referred to as analytical (such as the Activity Based Costing).

Despite its benefits, many factors are still preventing WLC costing from being used as the reference decision-making method (Gluch and Baumann, 2004). Table 2-1 summarizes the main advantages and disadvantages of WLC costing methodology.

Table 2-1 Advantages and disadvantages of WLC (adapted from Gluch and Baumann (2004))

PROS	✓ Every aspect considered in the evaluation is turned into a single unit (monetary) ✓ Based on the most important factors, it returns a suggestion of the aspects to be considered ✓ It simplifies multi-attributed alternatives ✓ Considers costs from a life cycle perspective
CONS	▪ General lack of motivation, owing to time and effort required ▪ Contextual factors, like non-favourable position of design teams ▪ Lack of universal methods for cost estimations ▪ Access to data with relevant quality and accuracy

There is not a general agreement on the modalities to show the results of a WLC cost model but rather a set of methodologies can be defined (Zoeteman, 2001):

1. Total Present Value (TPV): it corresponds to the sum of the discounted cash flows occurring over the period of analysis and it is used to compare two different courses of action.
2. Internal Rate of Return (IRR): it is the discount rate figure that makes the TPV equal to the initial investment. It is used to compare the profitability of one investment to alternative ones.
3. Annual Equivalent or Annuity (ANN): it is the constant annual expenditure that has to be supported every year to perform maintenance activities. It is useful to compare options with different life spans.

Another method to present the results is providing a cost profile that shows the level of expenditures for every year of the service life of the system. It is useful to assess visually when the major expenditures will be supported in the future, in order to develop a good financial plan (Atkins, 2011).

2.3 Application of WLC to the railway industry

The railway industry has its own specifications, since assets have extended life spans and investments are considerable. Decisions about projects and maintenance strategies need to be drawn from a whole life cost perspective.

The application of a long-term approach to the rail industry presents some specific challenges (Andrade, 2008):

- Lack of data on maintenance costs
- Lack of data on degradation of different components of the infrastructure
- The acquisition of data is not always timely for swift decision-making processes
- Assets degradation rates are slower than mechanical equipment ones, resulting in more time for data collection
- In case of asset breakdown, consequential costs can be difficult to assess

Another challenge of the industry is that every project needs to maintain or improve the reliability, availability, maintainability and safety of the network (RAMS) (Patra, 2009). This can be obtained only with the application of established engineering methods, concepts, techniques and tools over the whole life of the system (adapted from EN 50126, cited in (Patra, 2009)). However, in another work, (Patra et al., 2008) states that RAMS is one of the two types of uncertainty that affects LCC estimations.

The railway industry presents several levels of complexity, as the Figure 2-4 shows. Together with internal and external variability, it is worth to mention railway dispersion (people and assets are distributed over a large area), diversity, in terms of components behaviour and asset lives, and interactions between system components (Schmid, 2010).

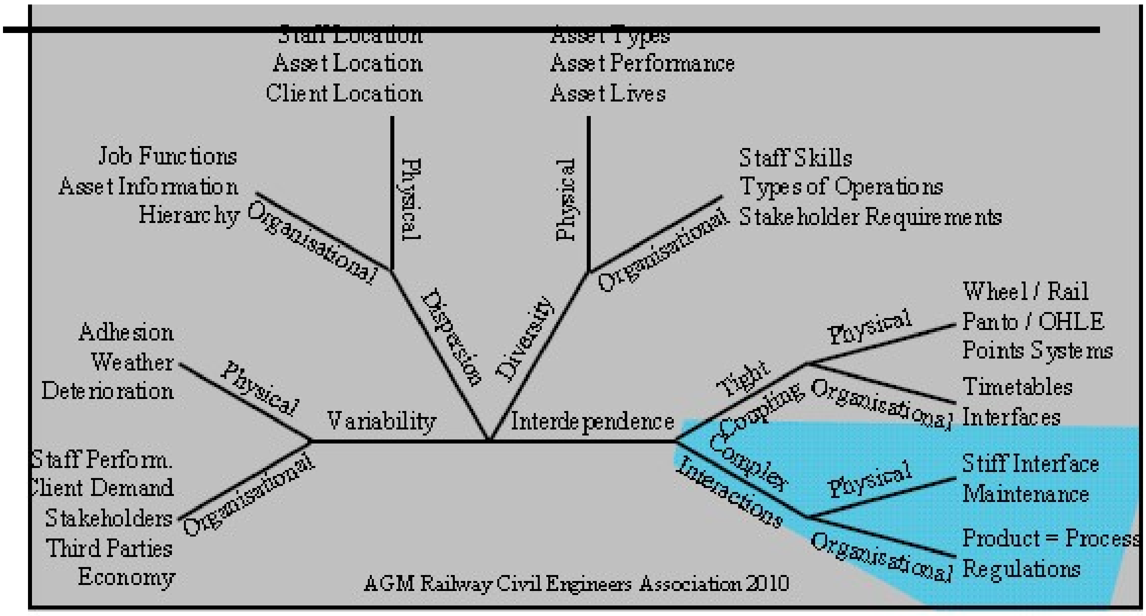

Figure 2-4 Railway complexity (Schmid, 2010)

2.4 Methodologies for WLC development

The literature offers several methodologies to develop a WLC cost model and the most relevant are listed in Table 2-2. The starting point is different according to different authors: Gluch and Baumann (2004) consider as priority the definition of the alternatives while Zoeteman and Esveld (1999) begin with the expected traffic flow of the route. The following steps are linked to the operational costs (maintenance costs, delay costs and possession costs). In order to consider uncertainties in the estimation of the parameters, it is good practice to include the sensitivity analysis before validating the model (Atkins, 2011; Ling, 2005).

Table 2-2 WLC development frameworks

(Gluch and Baumann, 2004)	1	Declaration of alternatives
	2	Identifying relevant economic and performance criteria
	3	Generating and grouping of significant costs for each alternative
	4	Risk assessment (future costs, inflation rates, life of components)
(Zoeteman, 2004)	1	Estimating the loads on the infrastructure components (years, train passages, tonnage)
	2	Estimating the periodic maintenance volume (shifts, amount of work etc.)
	3	Estimating total maintenance costs, possession and speed restriction hours

	4	Estimating the failure performances (journey time deviations)
	5	Estimating life cycle costs, availability and reliability per year
(Atkins, 2011)	1	Identify maintenance requirements
	2	Formulate alternative maintenance strategies
	3	Determine costs over the analysis period
	4	Calculate WLC on the basis of NPV
	5	Undertake sensitivity analysis
	6	Arrive at a preferred option
(Janz and Sihn, 2005 cited in (Ling, 2005))	1	Identify cost drivers
	2	Develop Cost Estimating Relationships
	3	Develop escalated and discounted life cycle costs
	4	Define an item or product life cycle
	5	Define activities that generate ownership costs
	6	Perform sensitivity analysis
	7	Establish cost profiles
	8	Determine cause-and-effect relationships
	9	Establish an accounting breakdown structure
(Zoeteman and Esveld, 1999)	1	Understand traffic volumes
	2	Estimate volumes of maintenance and renewal based on predicted track quality due to traffic volume
	3	Estimate possessions, speed restriction hour based on maintenance and renewal volumes
	4	Track possessions and speed restrictions are converted into an estimation of train delay minutes
	5	Cost are estimated for renewals and maintenance and for their influence on delays
	6	Costs are discounted over life
	7	Options are compared

2.5 WLC cost drivers

An activity or product cost driver is 'any factor that directly explains the cost incurred by the activity or product' (Ben-Arieh and Qian, 2003). According to Zoeteman (2004), WLC cost drivers can be grouped into construction costs, maintenance costs and, according also to Ling (2005), non-availability costs, with the latter depending upon the hours of track possession and speed restriction. Du and Karoumi (2013), together with maintenance and replacement costs, state that also monitoring and unexpected risks costs should be considered in project evaluations. While Kirkwood et al. (2014) focus the attention on downtime costs, Invensys Rail (2010) notices that in the railway industry more than one half of the WLC costs are represented by labour. In another work, Zoeteman (2001) affirms that maintenance and failure costs are driven by the degradation of the assets. Finally, though for Ling (2005) RAMS parameters are high level cost drivers, their uncertainty is a big factor determining WLC costs (Patra et al., 2008).

2.6 Railway maintenance

Maintenance activities and related costs are expected to be relevant factors of the model since tracks, bridges and OLE are assets with very long life spans. Nowadays, standards and regulations have become more restrictive and rigid in order to safeguard all the process stakeholders, so that strategies need to meet the best compromise between costs, asset reliability and risks (Tzanakakis, 2013), as illustrated in Figure 2-5.

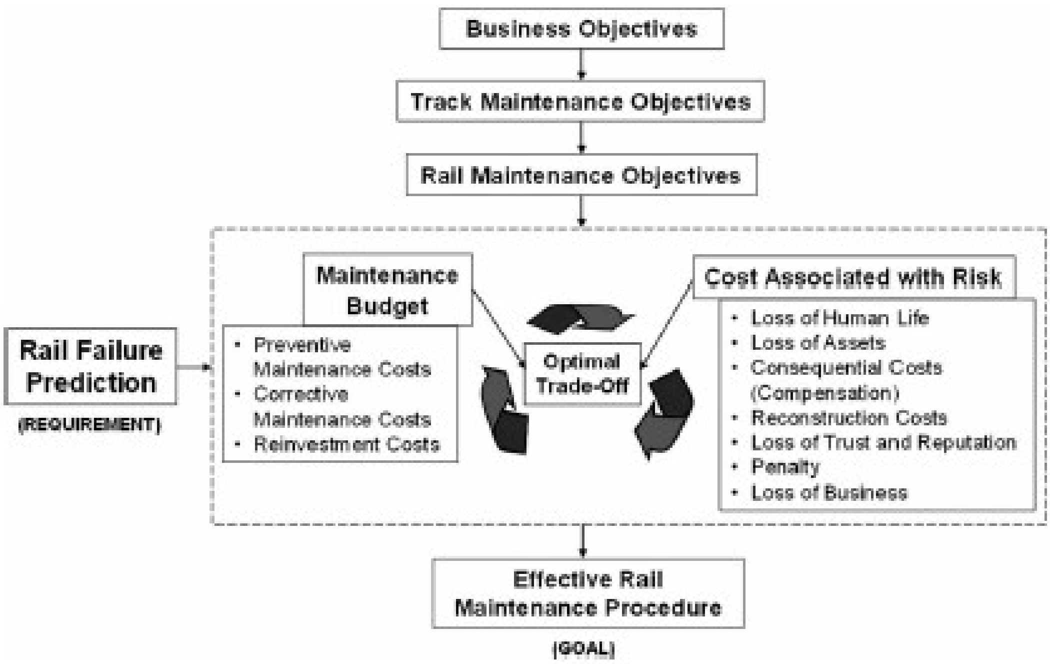

Figure 2-5 Process of developing an effective rail maintenance procedure (Kumar et al., 2008)

According to Tzanakakis (2013), four types of maintenance can be defined (Figure 2-6):

1. Run to failure Maintenance: the asset is repaired after breaking down
2. Preventive Maintenance: activities are performed before failures occur, at planned intervals of time or fixed criteria

3. Corrective Maintenance: activities are performed after the occurrence of failures, and the aim is to eliminate their source
4. Predictive Maintenance: it is a set of methods that helps infrastructure managers to predict when maintenance should be performed on the basis of the real conditions of the asset.

Condition-based maintenance is also found in the work of Kumar et al. (2008), who refer as to the use of sensors along the rails to gather real-time information about the state of track components.

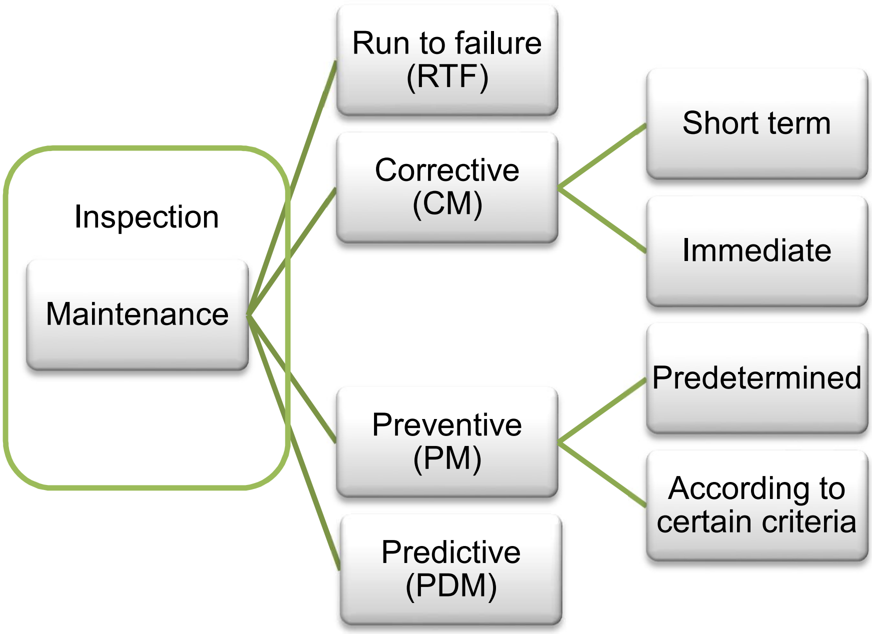

Figure 2-6 Maintenance strategies (rearranged from (Tzanakakis, 2013)

2.7 Asset degradation models

In order to estimate WLC costs, the factors that influence railway infrastructure performances are to be recognised. The main factor that drives failures and maintenance is represented by the degradation of the asset (Zoeteman, 2001). An asset degradation model describes how components or systems deteriorate their ability to perform required functions.

2.7.1 Tracks

There is a general concordance that tracks degrade according to a negative exponential-like equation (Jovanovic, 2005; Tzanakakis, 2013; Jovanovic et al., 2015). The analytical expression is a function of time even if the main responsible for degradation is rather the traffic flow on the route (MGT/year). In particular, the quality of the track (Q (t), %) over each year of the planning horizon (t, years) depends upon the quality at renewal time (Q_0, %), set conventionally at 100%, and upon the degradation rate (b, positive and dimensionless), as shown in equation (2-1) and Figure 2-7.

$$Q(t) = Q_0 * e^{-bt} \qquad \textbf{(2-1)}$$

Figure 2-7 The service life of tracks (Tzanakakis, 2013)

2.7.2 Overbridges

Regarding railway overbridges, an agreement between authors is harder to find. Most of the research has been carried out in relation to underbridges to assess how their structural properties change along with rail traffic. In addition, according to the material they are made of, life spans differ significantly (Le and Andrews, 2013). According to Hai Le (2014), it is possible to model the behaviour with Markov chains but, owing to the non-constant deterioration rate in reality, it is preferable to use a Petri-net approach. However, both models are not suitable for this thesis because of the high level of details required. A simpler model, that relates the condition of the asset to its age (Condition Rating), can be found in Le and Andrews (2013); the mathematical expression is a third-degree polynomial that returns for each year (t) a value out of a 0-to-7 scale.

$$CR(t) = 7 - 0.037553t - 0.0003374t^2 + 0.0000019t^3 \quad \textbf{(2-2)}$$

2.7.3 Overhead Line Equipment

Before discussing the literature about the asset degradation model, it is worth to give a brief description of the system.

According to Kim et al. (2007), an OLE is ‘an equipment installed overhead in order to supply electric power to […] rail vehicles’. It consists of several components, as shown in Figure 2-8:

- Contact wires, which are in contact with the pantograph head
- Messenger wires, which give above support to contact wires and maintain the stiffness uniform along the span
- Droppers, which link messenger wires to contact wires and keep the latter at a fixed height
- Steady arms, which maintain a zigzag shape of contact wires in order to prevent them from uneven wear

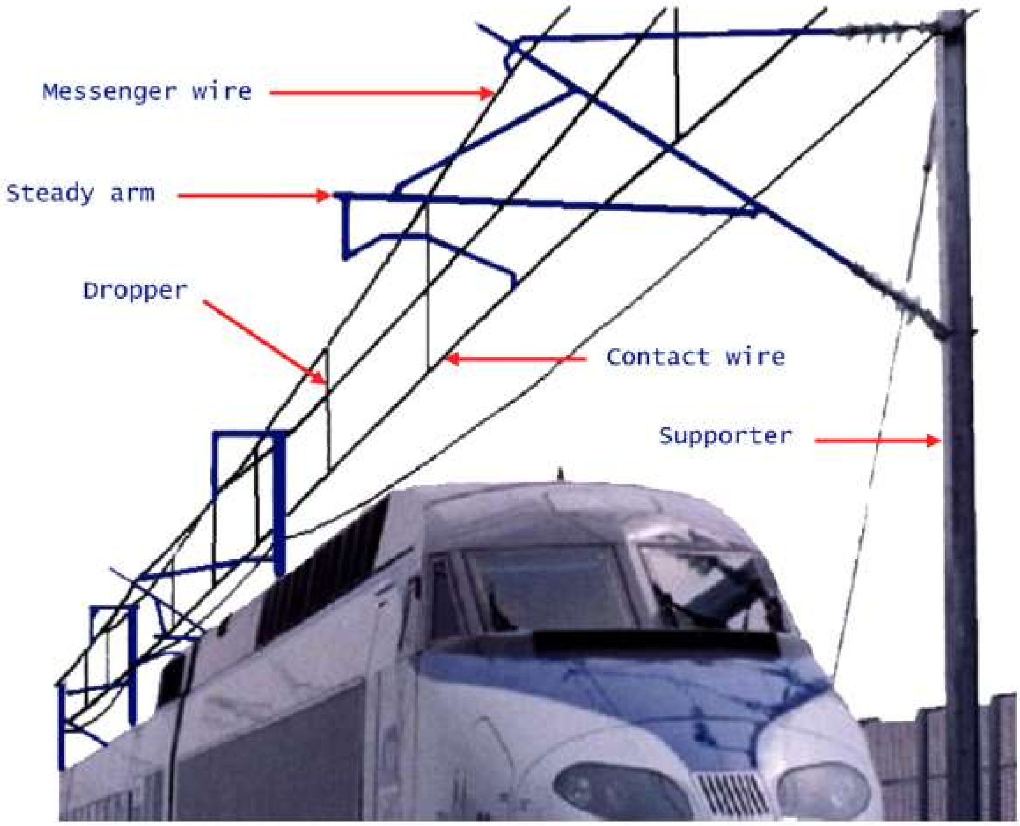

Figure 2-8 The structure of a catenary system of a high-speed vehicle (Kim et al., 2007)

The degradation process of the OLE system results not easy to analyse, since components are designed for different expectancies of technical life. Researchers have calculated the average life span of contact wires in 15 years (Shing and Wong, 2008), while the remaining components maintain their operations for 40 years or more (Shing and Wong, 2008; Atkins, 2011; Ho et al., 2006). For this reason, data from many past years are required in order to build a real system degradation model. For example, Duque (2009) uses records of system failures from the previous 17 years and finds that annual failure rates for different components are of very low orders of magnitude (Table 2-3). Analogous results and figures are also obtained by Ku and Cha ((2011).

Table 2-3 Mean values for six components failure rates per year (adapted from (Duque et al., 2009))

Component	Failure rate per year
Current carrying connection	$1.510 * e^{-6}$
Dropper	$3.080 * e^{-6}$
Feeder line	$1.626 * e^{-3}$
Pole	$7.875 * e^{-6}$
Tensioning device	$3.648 * e^{-4}$
Overvoltage protection device	$4.062 * 4^{-4}$

With reference also to Usuda (2007), it is difficult to estimate contact wires wear from a theoretical point of view. It can be demonstrated by empirical means that contact forces, amount of passing pantograph and contact losses are main factors of wires wear. Warburton (2013) links contact wire wear to the loss of its cross sectional area and suggests that renewal activities should be triggered once local wear approaches 25 to 33% of it.

For technical and economic reasons, contact wires are the only components that are not installed redundantly so that the required high availability implies effective maintenance plans overtime (Duque et al., 2009). They are in fact subjected to mechanical and electrical loads as a consequence of electric voltages and currents, and climate adverse conditions.

For all those reasons, many railway operators consider contact wire wear as a slow and gradual process, which becomes evident only after many years of abrasion. Rate of wear is deemed insignificant over a limited period of time and proceeds at a constant low rate (Shing and Wong, 2008).

From an analytical point of view, the Weibull distribution is considered a very good approximation of the asset behaviour overtime (Meier-Hirmer et al., 2006; Ho et al., 2006); however, it has been demonstrated that, in case of sparse data, also the exponential distribution gives satisfying results (Meier-Hirmer et al., 2006).

2.8 Climate changes

Climate changes are expected to have a great influence on railway system future modelling (Baker et al., 2010; Palin et al., 2013; Stewart et al., 2014). According to Baker et al. (2010), quantifications of the effects and methods for assessing the most critical ones are still lacking and it is in addition unknown how people attitude towards transports will change according to climate changes.

Predictions made on the basis of different emissions scenarios and for a 30 year time period centred on the 2020s, 2050s and 2080s (Baker et al., 2010), show that the United Kingdom should experience:

- Hotter and drier summers, with increased buckling, desiccation of track earthworks, growing vegetation due to longer growing season and changing tree shed times
- Warmer and wetter winters, characterised by increased flooding, damage to earthworks and track circuit problems due to higher water contents in the ballast
- Increased frequency of extreme storms, with increased likelihood of dewirements and derailments

The above factor list has an impact on the infrastructure options considered. Increasing flooding and leaves on tracks would negatively affect track lowering scenarios, while higher hours of maintenance would be required regardless of the option selected, together with increasing costs coming from speed limits and track possessions.

2.9 Case studies

The challenge the railway industry is facing regarding the extension of electrification to overbridges is not a novelty. During previous decade’s electrification plans, in fact, managers have already coped with non-sufficient electrical clearances under the ceiling of overbridges. The technical representation of electrical clearances is given in Figure 2-9.

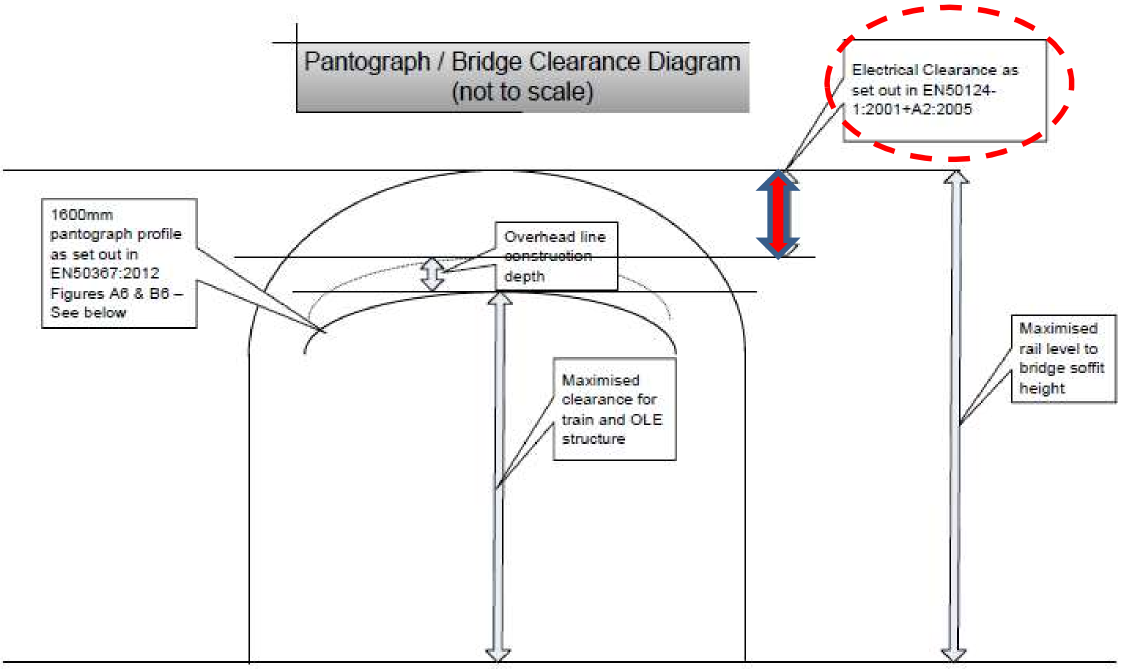

Figure 2-9 Pantograph-bridge clearance diagram (Future Railway, 2014)

Stevenson (1987) provided a description of the electrification on the London-Bedford route (1976-1981). Among alternative solutions, like third rail and full dieselization, the 25 kV AC option was considered the one with the lowest sum of discounted cash flows. Civil works accounted for the 28% of the total project costs, while the relevant alterations to overbridges were spread over five years to keep service disruption to a minimum. The adopted solutions adopted was chosen according to each single case (27 demolitions and reconstructions, 5 jack-ups, 8 removals, 8 track lowerings), underlying that generalizations are hard to achieve even on the same route. For example, in a tunnel near London, the required electrical clearances could not be provided by track lowering since the majority of the length presented brick invert (Figure 2-10), which were used in the past to give stability to the overall structure. In addition, the track slab option was preferred to normal ballast track for stability reasons.

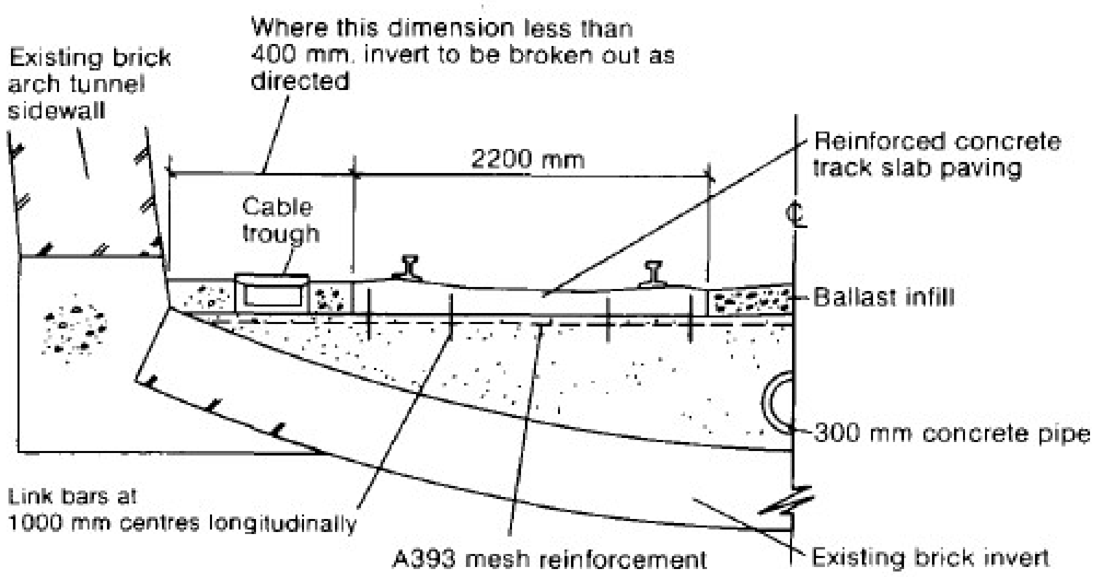

Figure 2-10 Tunnel structure with brick invert (Stevenson, 1987)

In Kentish town, the presence of services (275 kV cables) prevented managers from using precast concrete or bridge demolition. The decision was to lower the track, adopting a concrete slab track to provide additional lateral resistance as a consequence of poor conditions of the clay ground.

Another solution used on the route was the replacement of existing brick arches with a standard precast concrete ones, which have minimum construction depth and a design that takes into account the shape of the locomotive pantograph (Figure 2-11). In addition, if roads are present on the overbridge, the solution allows to close one lane at a time while keeping the other(s) one in service.

Another work of interest for the thesis is the one by Fenwick (1992), who described the electrification of the East Coast Main Line. In Bond Hill Ash Bridge (York), in order to alter minimally the carrying highway vertical alignments, the decision favoured the demolition and reconstruction with a standard concrete new one new deck. In Holgate Bridge (York), the selected solution was to jack-up the bridge, even if highway approaches and services were deeply altered. Other options were considered not economically feasible, especially track lowering because of the high number of tracks present (six). In Red Barn's Tunnel (Newcastle), track lowering was deemed the best option to follow.

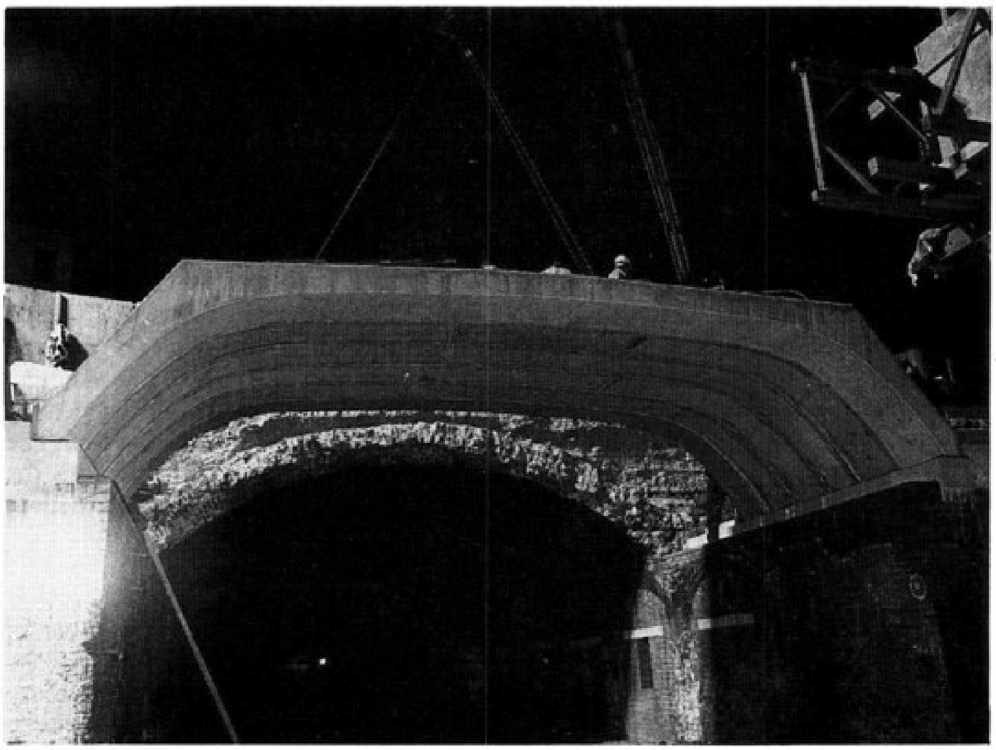

Figure 2-11 Precast concrete arch unit (Stevenson, 1987)

Regarding track lowering, it was decided not to install a concrete slab track but a ballasted one on a concrete slab, in order to perform the required maintenance activities in the traditional way (mechanical tamping), as Figure 2-12 illustrates.

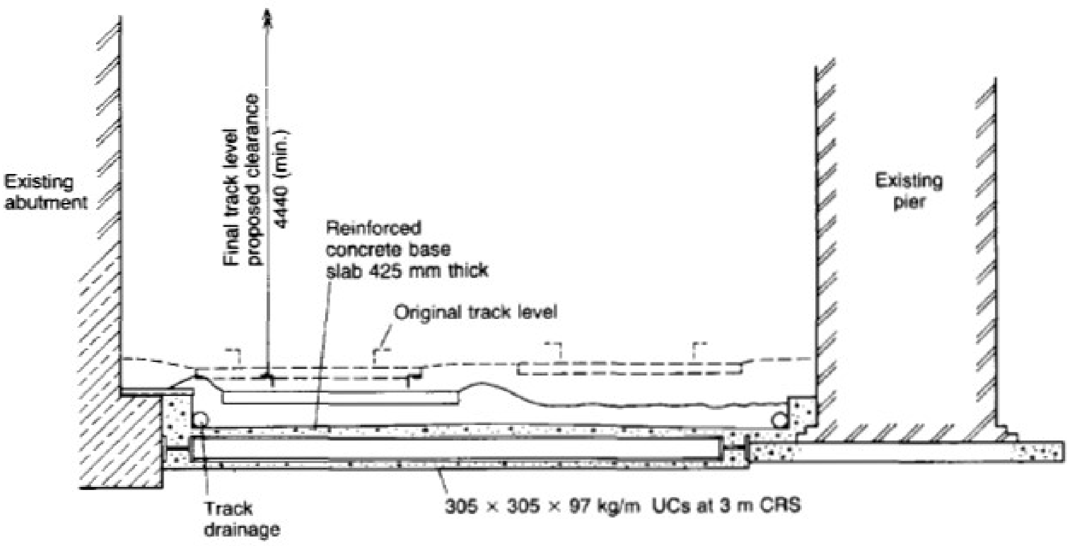

Figure 2-12 Engineering works for Newcastle Red Burns tunnel (Fenwick, 1992)

Other case studies can be found in the works of Macdonald et al. (2009) about the electrification project in Auckland (New Zealand). After listing all the possible solutions, the authors provided some examples of the overall engineering works (in total 42 overbridges to be altered). Even in these cases, adopted solutions followed considerations of several factors, like the conditions of existing overbridges, materials they were made of, ground conditions, carrying road traffic levels and rails profiles (presence of gradients). This is a further example that highlights generalizations are difficult to reach because every case study is treated singularly and many are the variables to take into consideration.

Finally, an innovative solution was proposed by researchers from the University of Birmingham (Hoffrichter et al., 2012). Using a University simulation software developed for the purpose, the authors assessed the feasibility of discontinuous electrification (adding neutral sections to the electrification system) to reduce electrification costs in presence of clearances issues. In particular, they assessed the impact of the solution on train performances and service quality. In fact, along with degrading services performance indexes, increasing delay costs should be considered as well. The simulation was conducted on a replica of the line between London Paddington and Cardiff Central and the main indicator of the success was considered the journey completion. The study concluded that journey times differed only by little (2-3%) between full electrification and partial electrification scenarios, and that the factors most affecting the results were the length of overbridges and tunnels and the train entering speed.

2.10 Research Gap Analysis

From the discussion of the results so far achieved by the research in relation to the topics of interest for this thesis, it is possible to deduce that:

- There is a lack of models that simultaneously consider the behaviour tracks, railway overbridges and OLE
- There is a need of a model to compare different electrification infrastructure options from a cost-benefit point of view
- Very little research has been carried out on the consequences of each option on the Whole Life Cycle costs supported by the infrastructure managing company

The consequences of the above stated considerations are represented in reality by the significant proportions that civil engineering costs for infrastructure modifications are estimated to be supported in the current electrification programme (Future Railway, 2014; Network Rail, 2009). The improved decision-making process through the use of the model is expected to bring advantages for all the project stakeholders, including the society, which reveals its hostility against legacy bricked-bridge demolitions.

2.11 Summary

This chapter has presented the results of the research about the topics relevant for the thesis. They are related to many aspects of the railway industry, from WLC cost modelling methodologies and challenges, to asset degradation models, discussing as well climate changes and case studies during previous electrification projects. The findings will be used for the development of the cost model (chapter 4) and software tool (chapter 5).

3 RESEARCH METHODOLOGY

3.1 Introduction

A structured methodology is a key component to achieve the aim and objectives of the thesis. In the case of this project, a five-step one has been followed, allowing for feedbacks and backtracks among the last phases. After starting with project definition and information acquisition to provide the background from the requirements and available research points of view, it proceeds with the two core elements, the cost model development and the related software tool. The methodology ends with the final validation of the tool through experts' judgements and suggestions for improvements. The complete structure of the methodology is presented in Figure 3-1.

3.2 Methodology description

Phase 1 is dedicated to 'Project definition'. This was the very first moment of the thesis, where several meetings were hold with the AUTONOM Project Cost Analysis team to define expectations and requirements. Aims and objectives were shaped accordingly, and the OLE maintenance database was provided. Then, followed contacts and meetings with the Collaborator Company, where it was possible to gain part of the knowledge about the current practices within the industry and Collaborator Company. The principal output of the phase was the development of the Client Research Brief, which is the formal document that described times, steps and methodologies that the student will follow for the successful completion of the research.

The second step was titled 'Information acquisition' and elapsed from the beginning of May to mid-June, though some information were also searched during following phases. The principal activity was the Literature Review, whose aim is to critically discuss what has been already achieved by researchers and companies on the topics of interest for the thesis. It resulted a quite prolonged activity, since the information to be gained referred to many different topics. For this reason, more than eighty documents were analysed, from journal papers to companies' white papers. Other activities were carried out during this phase: from

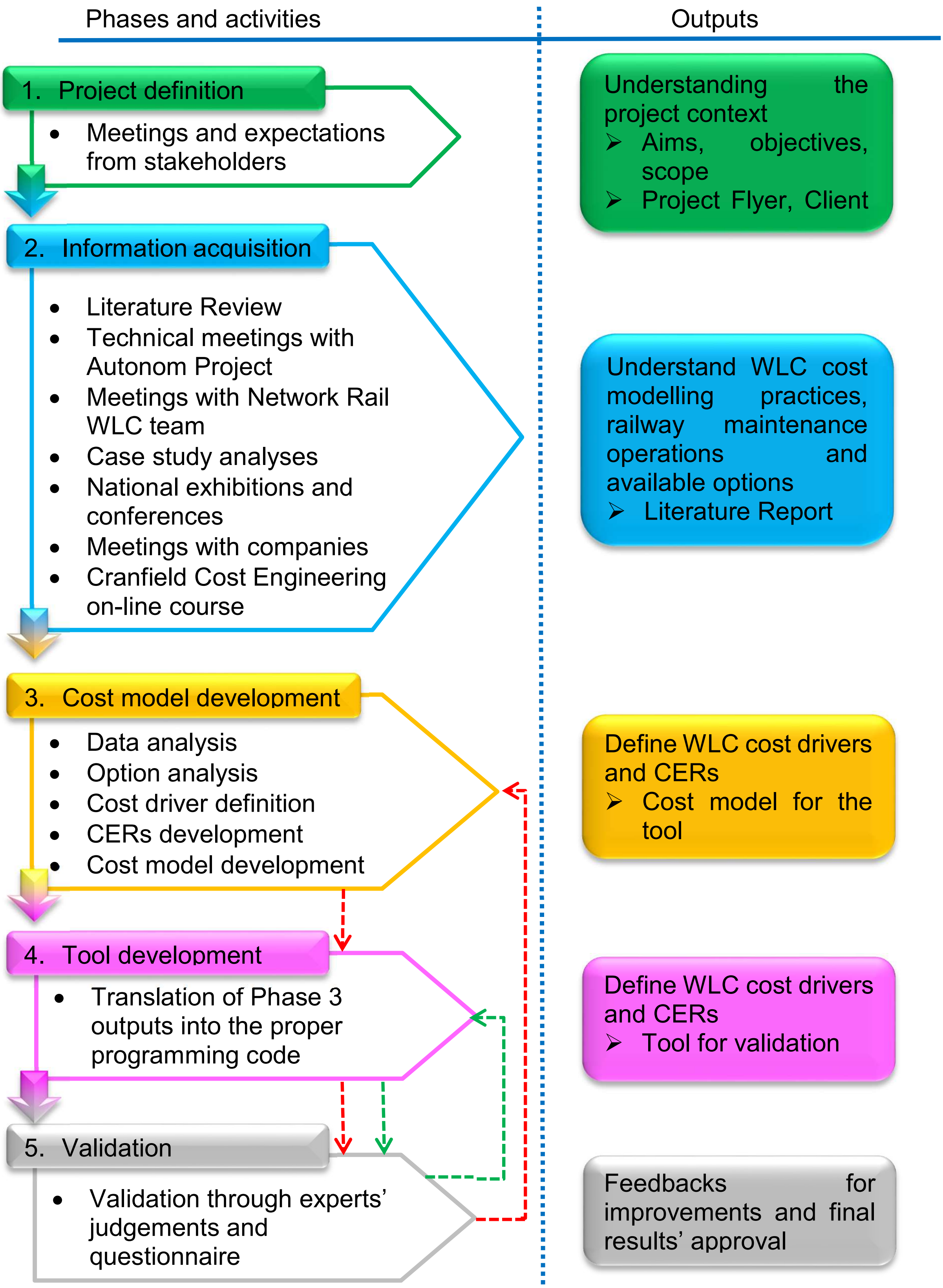

Figure 3-1 Research methodology structure

previous case study analysis to national conferences and exhibitions, together with meetings with civil engineering companies operating in the industry. These last three activities were particularly useful to better understand the background of the thesis and realize the importance of the challenges of electrical clearances. In particular, it was possible to contact directly two of the companies that had taken part in the Avoidance of Bridge Reconstruction Project (Future Railway, 2014); however, the results of the meetings were not discussed within this thesis due to non-disclosure agreements and because one of the solutions proposed had not been tested yet. Finally, resulted very helpful an online Cost Engineering course provided by Cranfield University, which gave a wider understanding of the methods and practices to follow when costs are to be estimated in future scenarios The findings from the literature and case studies were summarised in the Literature Report.

Once the information were gained from different sources, the project proceeded with the first core step, the ‘Cost model development’. First, the database given by the AUTONOM project was analysed in order to extract information. In particular, it returned an average figure that was useful to model the maintenance costs for OLE, according to the parametric estimation method. Then, followed a technical analysis of the infrastructure options that were considered of interest by the Collaborator Company focusing on the implications of each one on the WLC costs. Afterwards, the structure of the model was described, expressing the rationales behind decisions taken, with particular mention to the development methodology, group of costs and assets to be considered. The definition of the WLC cost drivers followed shortly after, together with the decisions about the ones to be included in the analysis on the basis of the information available. Cost drivers were eventually linked to total costs through a set of equations. The last activity of the phase was the definition of the assets degradation models, as suggested by the methodologies found in the literature. Specifically, it was defined how to link the condition of the assets to each single year of the project planning horizon. At that point, the cost model was ready to be transferred to the following phase.

In order to improve the decision-making process on the basis of the cost model developed, a MS 2013 Excel-based tool was developed (Phase 4). Though not formally stated within the beginning requirements, the author felt of utmost importance to provide a software tool, given the quantity of calculations required to obtain the results. This decision was also justified by the literature, which in the major part of the cases showed the presence of a tool directly related to the cost model developed. After translating the cost model into the mentioned tool, remarkable effort was put on the decisions regarding the best way to display the results. The outputs of the phase was the completion of the software, whose main advantages resulted the automation of the decision-making process and the clear visualization of the WLC costs by bar histograms.

The last step of the methodology is the 'Validation phase'. This is a necessary step to assess whether the model does meet the requirements set by the stakeholders and perform the right calculations. In the first instance, one trial was run with two different scenarios to check whether it did not belie the supposition made in earlier steps by the Collaborator Company. However, a standard sensitivity analysis resulted not possible to be carried out, since the model included some assumptions about parameters that would invalidate any possible conclusion. The tool was presented to a group of Autonom Project representatives through three different validation sessions, with the aim of judging the results of the research and capturing feedbacks for improvements.

3.3 Summary

This chapter has presented how the research was structured throughout the project development. For each phase, aim, activities performed and main outputs have been presented. The flow chart also explains were backtracks should be considered in order to integrate and refine the model according to the feedbacks provided by the stakeholders.

4 COST MODEL DEVELOPMENT

4.1 Introduction

This chapter represents the core of the project and explains in details all the steps followed for the development of the cost model. It also creates the basis for the software-based tool presented in Chapter 5.

After analysing the model requirements set by project stakeholders, a discussion of current practices within the industry and a description of the options for infrastructure modifications are provided, focusing on the expected consequences on WLC costs. The structure and methodology used for model development are then presented, followed by the activities carried out during the data analysis phase. The chapter ends with the description of the WLC cost drivers and with a discussion of the asset degradation models used.

4.2 Industry's current practices and requirements

The requirements for the cost model and related software-based tool were defined during technical meetings and informal conversations with representatives from the Collaborator Company and AUTONOM Project Cost Analysis team. They were in addition aligned with current practices within Network Rail, Britain's railway infrastructure owner and managing company (Chapter 3, Phase 1).

With the beginning of Control Period 5 (2014-19), the ORR and Network Rail set WLC as the mandatory methodology to assess any railway project. In particular, WLC has been defined as the sum of non-construction costs, income and benefits and LCC costs, as shown in Figure 4-1. It is worth noting the consideration of safety risk costs (related to hazards to people) and disruption costs, which in turn consist of delay, possession and service risks costs (related to assets failure rates).

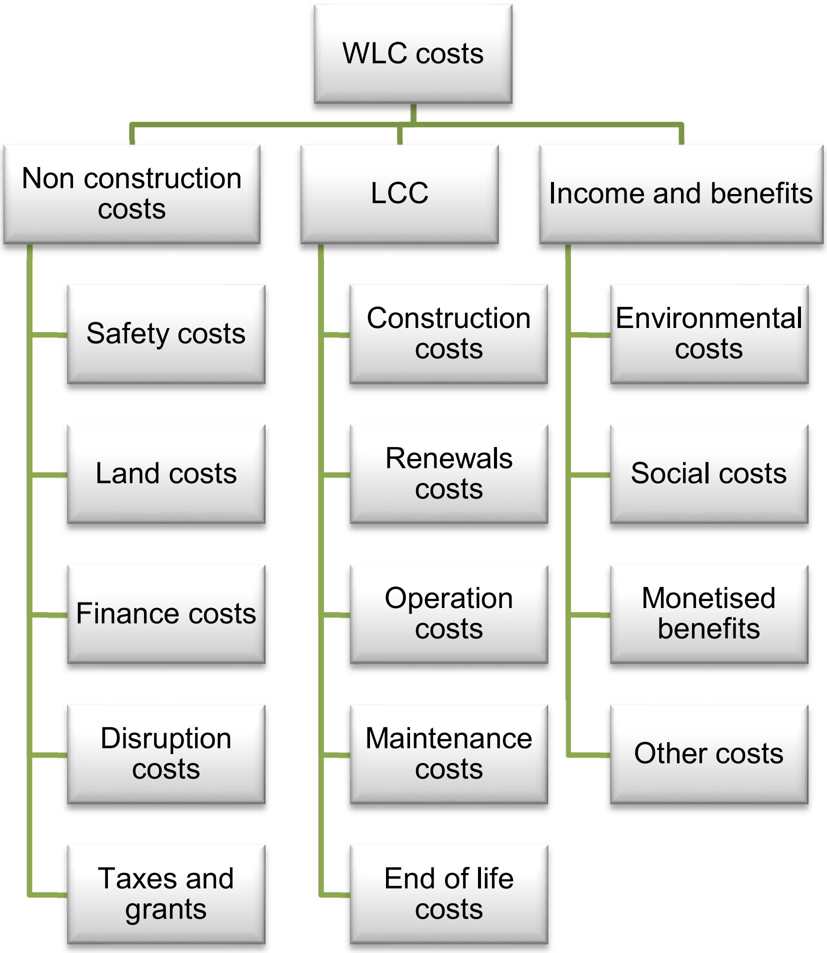

Figure 4-1 WLC cost components

The adoption of a full WLC cost model rather than a LCC one depends upon the scope and stage of the project (called GRIP, Governance for Railway Investment Projects) (Figure 4-2). When projects involve the existing asset basis (e.g. single asset renewals or simple enhancements), evaluations on LCC basis would be sufficient, while for complex enhancements or multi-asset renewals an assessment on WLC is conversely considered mandatory. One the other hand, WLC analysis are to be used during each stage of the project (from feasibility studies to end of life), but especially in the last phases (when the asset is in service) the emphasis is put on LCC.

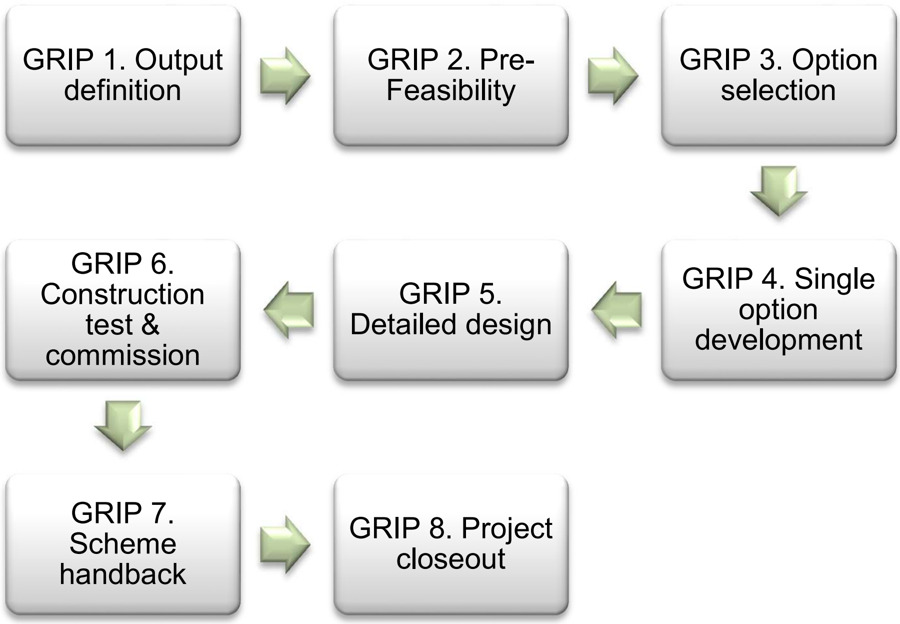

Figure 4-2 GRIP lifecycle (adapted from (Network Rail, 2015c))

According to Network Rail practices, the methodology to build a WLC cost model is:

1. Define the lifecycle stage
2. Define the asset, from a single component to a network of multiple assets
3. Define activities and asset interventions for each stage of the lifecycle
4. Specify asset behaviours, by introducing asset degradation models and failure rates
5. Set global parameters: discount rate, costs of service disruption
6. Select outputs, comparing the NPV across several scenarios
7. Sensitivity and uncertainty: assign distributions to input parameters and run a Monte Carlo simulation to provide a range of outputs for each project

In this framework, the ORR set the minimum planning horizon and the discount rate in respectively 60 years and 4.31%. The expected output of a WLC model is the NPV of the project, which equals the TPV less the initial investment (I_0, £) (equation (4-1)): the cash flows (CF_t, £) occurring over each year (t, years) of the planning horizon (n, years) are discounted according to the fixed rate (r, %) and then summed up together.

$$NPV = -I_o + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \qquad \textbf{(4-1)}$$

The output is showed in a graphic form, preferably with a histogram where bars correspond to each different project option NPV, calculated with equation (4-1).

4.3 Option analysis

In order to increase the expected gap between electrified cables and overbridge ceilings, infrastructure alterations to the railway infrastructure are required. The civil alterations assessed by the model were defined during meetings (phase 1 of the research methodology) with the AUTONOM Project Cost Analysis team, the literature and official websites of UK railway projects (Future Railway, 2014). Three options were deemed the most relevant for the evaluations and should be treated as mutually exclusive within this work (Figure 4-5).

4.3.1 Bridge demolition and reconstruction

In this first scenario, capital expenditures are represented by demolition, reconstruction of the overbridge (Figure 4-3 is an example) and OLE installation costs. It allows for the greatest level of clearances and the amount of maintenance required for each asset depends directly upon its condition. However, especially in the case of Victorian masonry arch bridges replaced by new and colder steel ones, the solution is not very well seen by people living in the nearby for aesthetic reasons.

Figure 4-3 Bridge demolition and reconstruction (Future Railway, 2014)

4.3.2 Track lowering

During 'year 0', existing rails and ballast are first removed to allow for digging the soil on both sides of the overbridge. A new drainage system is put in place, together with new ballast and new rails. This solution involves considerable denial of service costs, especially during initial engineering works, and greater maintenance levels for tracks, because rails, ballast and drainage are affected by stagnating water during rainy periods (Figure 4-4). Though the bridge is not demolished, the high level of maintenance represents a potential issue as less availability of track possessions are expected in the future.

Figure 4-4 Track lowering scenario (Future Railway, 2014)

4.3.3 Reduced clearances

This solution presents the lowest initial investments as no substantial alterations are required, but prevents the infrastructure owner company from upgrading for future speed improvements. OLE installation is conversely more expensive because of flash-over protections installed under the ceiling to diminish the quantity of trips on the line (especially due to birds hitting live cables). In addition, the height of the cables under the overbridge is lower than on open routes so that a gradient is present while approaching the bridge. These two facts generate an increased amount of maintenance on contact wires as a consequence of the greater forces exchanged with pantographs. The ‘reduced’ clearance level is additionally more restrictive on tracks longitudinal and vertical movement allowances so that more tamping activities are to be considered to keep the rail positions within the prescribed boundaries. Finally, specific concerns regard restricting future maintenance due to less availability of possession times, and increase fault occurrences because of the proximity of live cables and trains and ceilings, leading to greater downtime to passenger services and reputational negative impacts. However the impacts of all the mentioned characteristics on Whole Life Cycle costs are still not completely understood.

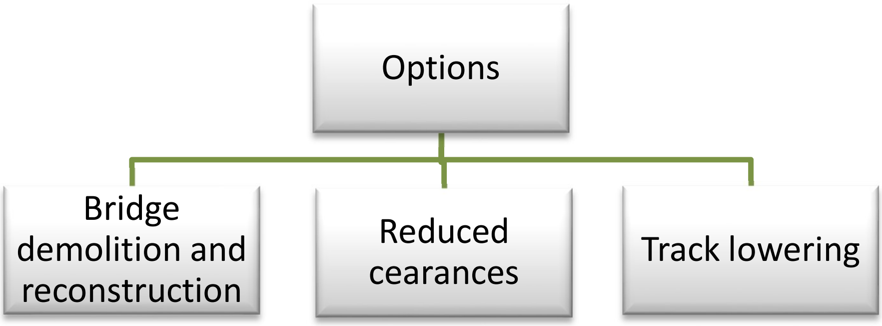

Figure 4-5 Infrastructure considered by the model

4.4 Cost model concept

The concept of the cost model is similar to a generic process schematization, as illustrated in Figure 4-6. With methods and constraints (or assumptions), inputs are turned into outputs according to rules, frameworks or equations. In this case, the inputs are data related to assets conditions, route features, times and costs from past projects, while the outputs are the WLC costs over the next sixty years for each considered option. In particular, the developed software-tool shows outputs with a histogram bar that enhance options comparisons.

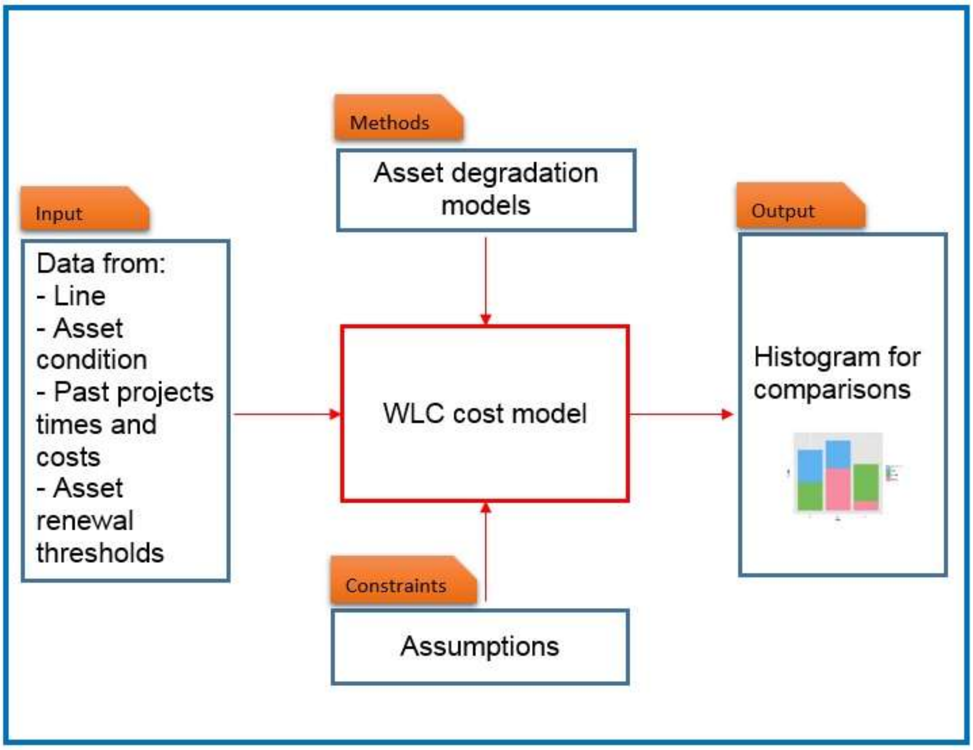

Figure 4-6 Cost model structure

The model was developed following the methodology showed in section 4.2 and was further integrated at the fourth point with additional four steps proposed by Zoeteman (2001) (Figure 4-7). These last ones are important because they link directly the behaviour of the asset to the expected traffic flow, (MGT) and consist in:

1. Estimating the loads of the track section:
    a. Expected traffic flow
    b. Current conditions of the assets
    c. Renewal threshold figures for all the assets
    d. Costs and duration of engineering works and maintenance activities
    e. Disruption unit costs for the track section
    f. Current features of the track (number of tracks, length of the overbridge)
2. Estimating assets conditions for each year of the planning horizon, based on asset degradation models
3. Estimating total maintenance costs, based on assets condition
4. Estimating life cycle costs, by summing up all the costs supported every year

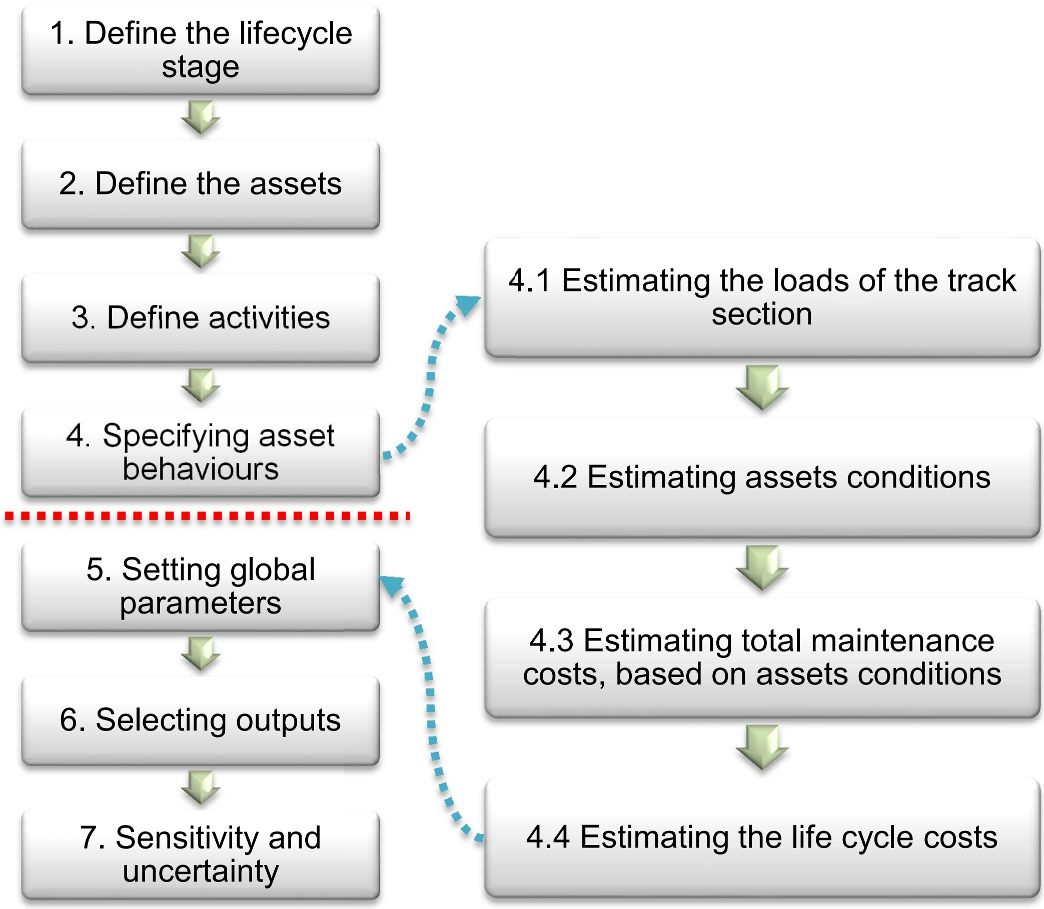

Figure 4-7 Flowchart of the developed model

The main project this work belongs to is the extension of the railway electrification (GRIP 2), which is the option chosen to increase the capacity of the existing network (GRIP 1). This thesis belongs to GRIP 3, which is still an early phase where the use of parametric techniques for costs estimation is considered as the most suitable. Costs are calculated on the basis of the asset conditions, in line with practices within the AUTONOM Project, whose major objective is to evaluate the feasibility of condition-based maintenance strategies. Therefore, asset degradation models are defined for the three assets (section 4.7) involved in infrastructure alterations: tracks, overbridges and OLE. This set of assets defines furthermore the model level of details.

In order to compare the three options equally and consistently over the whole planning horizon, group of costs (section 4.6), activities and related costs were defined.

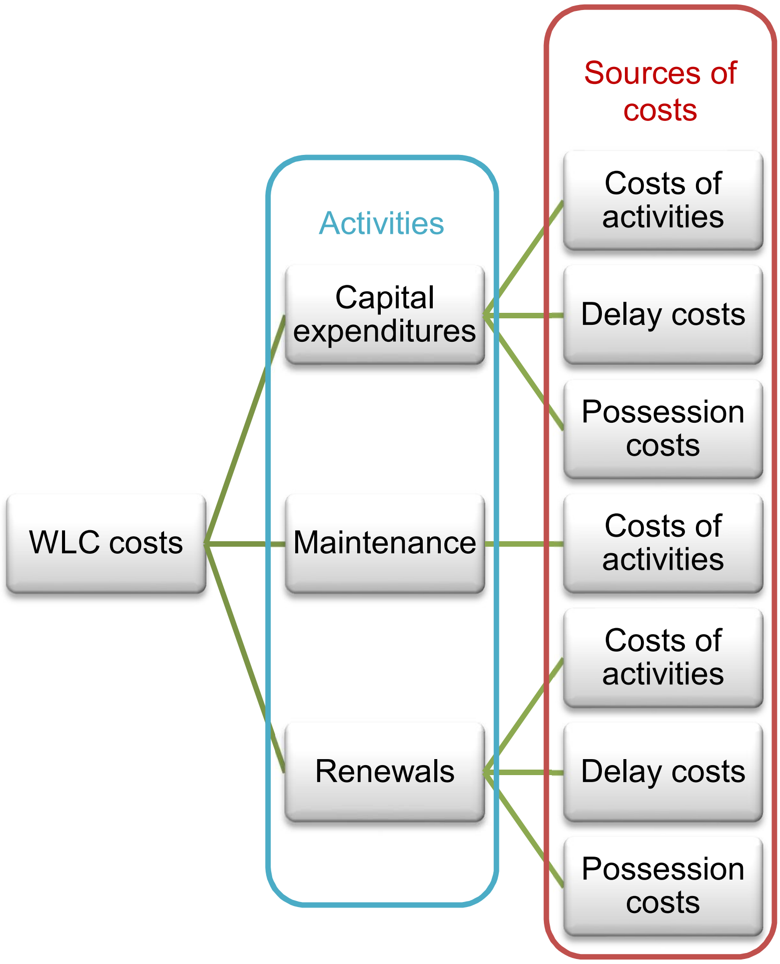

Figure 4-8 Activities and groups of costs for the model

Steps 5 and 6 of the development methodology have been already discussed in section 4.1, but it is worth underlying that most of the parameters cannot be set in advance but are to be defined according to every single business case. Case studies show, in fact, that every single section of route has its own features and each parameter can have an influence on the final decision. This consideration will be in practice turned into a requirement for the following software tool, which will need to be developed as a parametric.

Costs are finally summed up by year and then discounted back to the moment of the evaluation. The ones occurring in initial 'year 0' are considered CAPEX, while all the other are labelled as 'maintenance costs'.

4.5 Data analysis

The Collaborator Company provided a database with maintenance activities performed on the OLE system during Control Period 4 (2009-2014). The aim of data analysis is to extract information to model OLE maintenance costs. The general conclusion that can be drawn after the elaboration are:

- Faults related to overbridge are just a small percentage of total OLE ones
- Faults at overbridges are mainly caused by flash-overs in built-up area, causing roosting birds
- The majority of the causes for OLE faults are recorded as 'unknown'

Nevertheless, the given database allows to return an average figure for the hours spent on OLE maintenance activities. As stated in the previous section, this thesis belongs to an early phase of the electrification project, where parametric cost modelling is deemed as the most appropriate to deal with scarcity of data and uncertainties. Modelling maintenance costs on the hours spent, results therefore feasible and moreover strengthened by the literature, because it considers the railway industry as a labour-intensive business.

Data were filtered by asset types and the figures related to overbridges returned. The records were related to 60 different overbridges belonging to the same route. These two facts allowed on one side to work by averages (the sample size is statistically large) and on the other to gain information regarding the same type of OLE. In fact, different OLE systems are currently installed on different routes; this means that, if the data were related to different routes, or the sample size would be smaller or general conclusion could not be drawn. The results of the analysis is an average figure for the hours spent every year in OLE maintenance activities in overbridges.

4.6 Cost drivers

Costs in the railway industry are generally calculated per unit of track length (STK) but the data provided, conversely, did not allow computations in such unit of measure. For this reason, the majority of costs are estimated for ‘track section’, which in this work is intended as the part of the track that is covered by the overbridge. The definition implies that the starting and ending points of overbridges and tracks section are coincident.

WLC cost drivers are defined according to the relevant findings in the literature and current practices within the industry. In particular, five groups are identified, as shown in Figure 4-9:

Figure 4-9 WLC cost drivers

4.6.1 Capital expenditures

Capital expenditures occur during the initial years of the project, but the assumption is that they are supported entirely during initial ‘year 0’. In all the three scenarios, they include standard OLE installation costs, though in the third one an increment has been considered to account for the additional flash-over protections. The other two groups are demolition and reconstruction costs (first scenario), track lowering and drainage costs (second scenario). Table 4-1 correlates the type of CAPEX costs to the scenario in which they are considered.

Table 4-1 Capital expenditures for each scenario

	Costs		
	Demolition and reconstruction	Track lowering, drainage	OLE installation
Bridge reconstruction	X		X

Track lowering		X	X
Reduced clearances.			X*

Analytical expressions are described in equations (4-2)-(4-6).

$$\begin{aligned} &\mathit{Demolition\ and\ reconstruction\ costs}\ [£] \\ &\qquad = \mathit{Value\ set\ by\ the\ Collaborator\ Company} \end{aligned} \tag{4-2}$$

$$\begin{aligned} &\mathit{OLE\ initial\ investment}\ [£] \\ &\qquad = \mathit{Number\ of\ tracks}\ [\mathit{tracks}] \\ &\qquad * \mathit{Length\ of\ the\ overbridge}\ [\mathit{miles}] \\ &\qquad * \mathit{Electrification\ costs}\ \left[\frac{£}{\mathit{mile} * \mathit{track}}\right] \end{aligned} \tag{4-3}$$

$$\begin{aligned} &\mathit{OLE\ initial\ investment\ (reduced\ clearances)}[£] \\ &= \mathit{Number\ of\ tracks}\ [\mathit{tracks}] * \mathit{Length\ of\ the\ overbridge}\ [\mathit{miles}] \\ &* \mathit{Electrification\ cost}\ \left[\frac{£}{\mathit{mile} * \mathit{track}}\right] \\ &* \left(1 + \frac{\mathit{Increase\ in\ capital\ and\ renewal\ costs\ in\ red.cl.scenario}\ [\%]}{100}\right) \end{aligned} \tag{4-4}$$

$$\begin{aligned} &\mathit{Track\ lowering\ costs}\ [£] \\ &= \mathit{Distance\ to\ be\ lowered}\ [\mathit{miles}] \\ &* \mathit{Track\ lower\ ballast\ permanent\ way\ works}\ \left[\frac{£}{\mathit{mile} * \mathit{track}}\right] \\ &* \mathit{Number\ of\ tracks}\ [\mathit{tracks}] \end{aligned} \tag{4-5}$$

$$\begin{aligned} &\mathit{Track\ drainage\ costs}\ [£] \\ &\qquad = \mathit{Distance\ to\ be\ lowered}\ [\mathit{miles}] \\ &\qquad * \mathit{Drainage\ works\ per\ route}\ \left[\frac{£}{\mathit{mile}}\right] \end{aligned} \tag{4-6}$$

4.6.2 Maintenance costs

Maintenance costs are supported by managing companies to keep the system performing the desired functions. With references to the AUTONOM Project practices, they are modelled according to the conditions of the assets with a linear dependence (tracks and overbridges), while for OLE they are considered constant overtime and proportional to the average hours spent per overbridge. At the current stage of the project, it is not possible to distinguish between preventative and corrective maintenance costs, so that they appear summed into a single value.

For tracks and overbridges, the analytical expressions are listed below:

$$Track\ maintenance\ costs\ (t)\left[\frac{£}{year}\right] \tag{4-7}$$
$$= Number\ of\ tracks[tracks]$$
$$* Annual\ track\ maintenance\ costs\ (when\ new)\left[\frac{£}{year * track}\right] * 100$$
$$: Condition\ of\ the\ asset\ (t)\ [dimensionless]$$

$$Overbridge\ maintenance\ costs\ (t)\ \left[\frac{£}{year}\right] \tag{4-8}$$
$$= Annual\ overbridge\ maintenance\ costs\ (when\ new)\left[\frac{£}{year}\right] * 100$$
$$: Condition\ of\ the\ asset\ (t)[dimensionless]$$

The ‘annual track maintenance costs (when new)’ figure is to be entered by model-users because it varies according to different track types. For overbridges, conversely, the figure is obtained from a research study made by Le and Andrews (2013). The article provides an indication of the cumulated costs supported for railway overbridges over a period of sixty years, according to the maintenance strategy chosen. In this case, it was decided to reproduce the costs linked to ‘Strategy 2 (w/opportunistic)’ because, ‘components are repaired when they reach the poor condition’ (represented by dotted line in Figure 4-10), fact that considers again asset condition as trigger for activities.

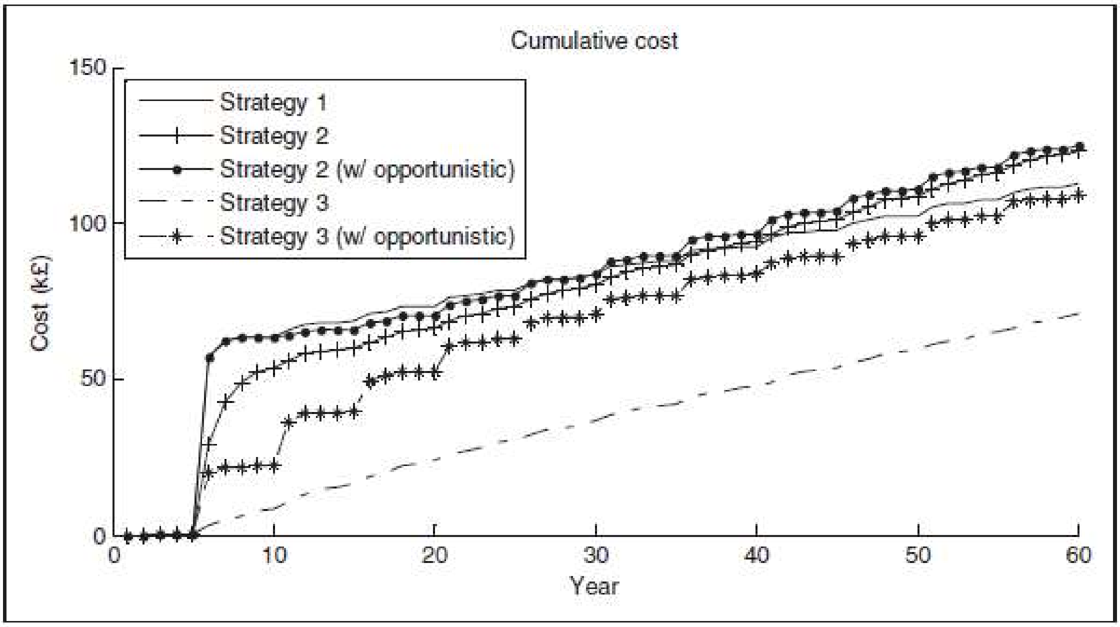

Figure 4-10 Cumulative expected maintenance costs for all repairs strategies (Le and Andrews, 2013)

The above graph has been plotted on Excel and the best interpolating equation chosen from the ones proposed in Table 4-2.

Table 4-2 Equations for bridge maintenance costs

Baseline	Equation	R^2
Exponential	$y = 57.98 * e^{0.0121x}$	0.9762
Linear	$\mathrm{y} = 0.9508\mathrm{x} + 55.492$	0.9839
Logarithmic	$y = 19.515\ln(x) + 19.078$	0.9367
Polynomial	$y = -0.0025x^2 + 1.0767x + 54.216$	0.9846
Power	$y = 35.999x^{0.2527}$	0.9606

In particular, the equation adopted was the linear approximation because of its easiness of management (Figure 4-11), despite the polynomial one presents a slightly greater R^2 value.

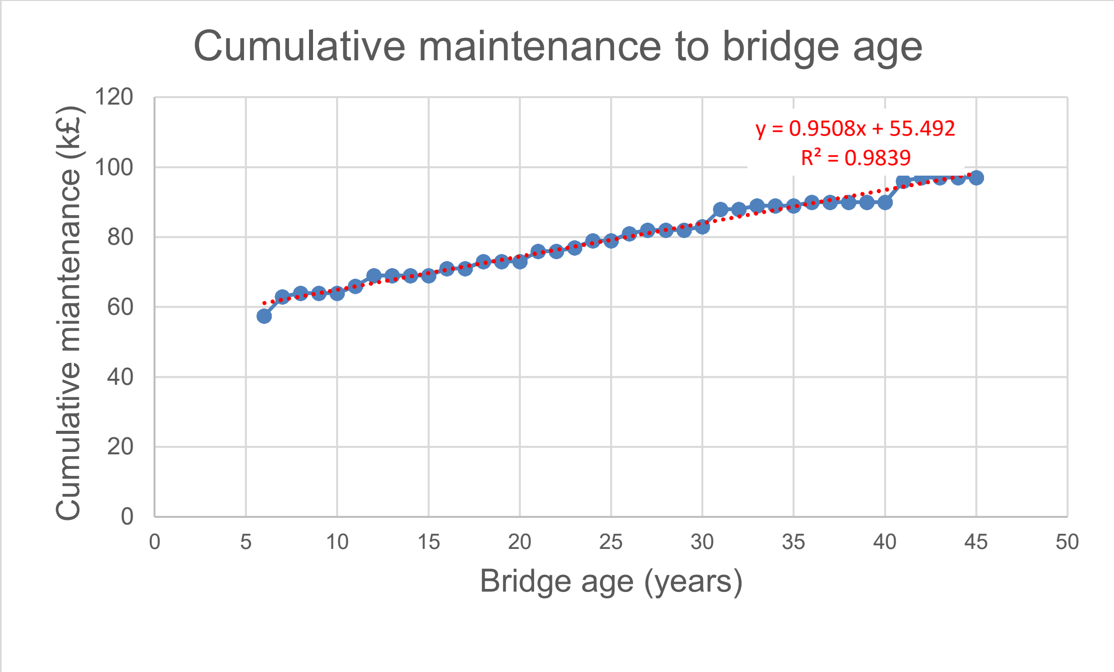

Figure 4-11 Cumulative maintenance costs (adapted from (Le and Andrews, 2013))

After the initial year, where renewals are performed, costs increase by £950 each year. But, in order to relate the costs to the condition of the asset like for tracks, the above value has been considered the 'maintenance cost (when new)', and thereafter they increase linearly with bridge condition.

For OLE, maintenance costs are modelled according to the parametric estimation methods, as written in equation (4-9). From the Collaborator Company's OLE database, it has been possible to extract the information required.

$$\begin{aligned} &OLE\ maintenance\ costs\ [£] \\ &\quad = Annual\ maintenance\ hours\ \left[\frac{hours}{track * year}\right] \\ &\quad * OLE\ maintenance\ costs\ \left[\frac{£}{hour}\right] \\ &\quad * Number\ of\ tracks\ [tracks] \end{aligned} \tag{4-9}$$

4.6.3 Renewal costs

Renewal costs are triggered when the condition of the asset falls below the renewal threshold. For overbridges, the value is to be entered by model users, while for tracks and OLE they are proportional to the length of the overbridge. The analytical relations are expressed through equation (4-10), (4-11) and (4-12).

$$Track\ renewal\ costs\ [£] \quad \textbf{(4-10)}$$
$$= Rail\ renewal\ costs\ \left[\frac{£}{mile * track}\right]$$
$$* Length\ of\ the\ overbrigde\ [miles]$$
$$* Number\ of\ tracks[tracks]$$

$$OLE\ renewal\ costs\ [£] \quad \textbf{(4-11)}$$
$$= Length\ of\ the\ overbridge\ [miles] * Number\ of\ tracks\ [tracks]$$
$$* \left(Removal\ of\ along\ track\ equipment\ \left[\frac{£}{mile * track}\right]\right.$$
$$\left. + Installation\ of\ new\ along\ track\ equipment\ \left[\frac{£}{mile * track}\right]\right)$$

$$Bridge\ renewal\ costs\ [£] = To\ be\ entered\ by\ the\ user \quad \textbf{(4-12)}$$

4.6.4 Delay costs

Delay costs are supported when speed restrictions on tracks are set by infrastructure managing companies. They are paid to TOCs for causing trains to delay and for consequently decreasing their PPM indexes. They are linearly dependent with the time lost by each train running the line. For delay but also for possession costs (section 4.6.5), the ‘bottom-up’ approach has been used, because it allows to consider all the parameters entered for the line, while a parametric estimation would provide the same value for each case. Figure 4-12 shows the costs breakdown structure.

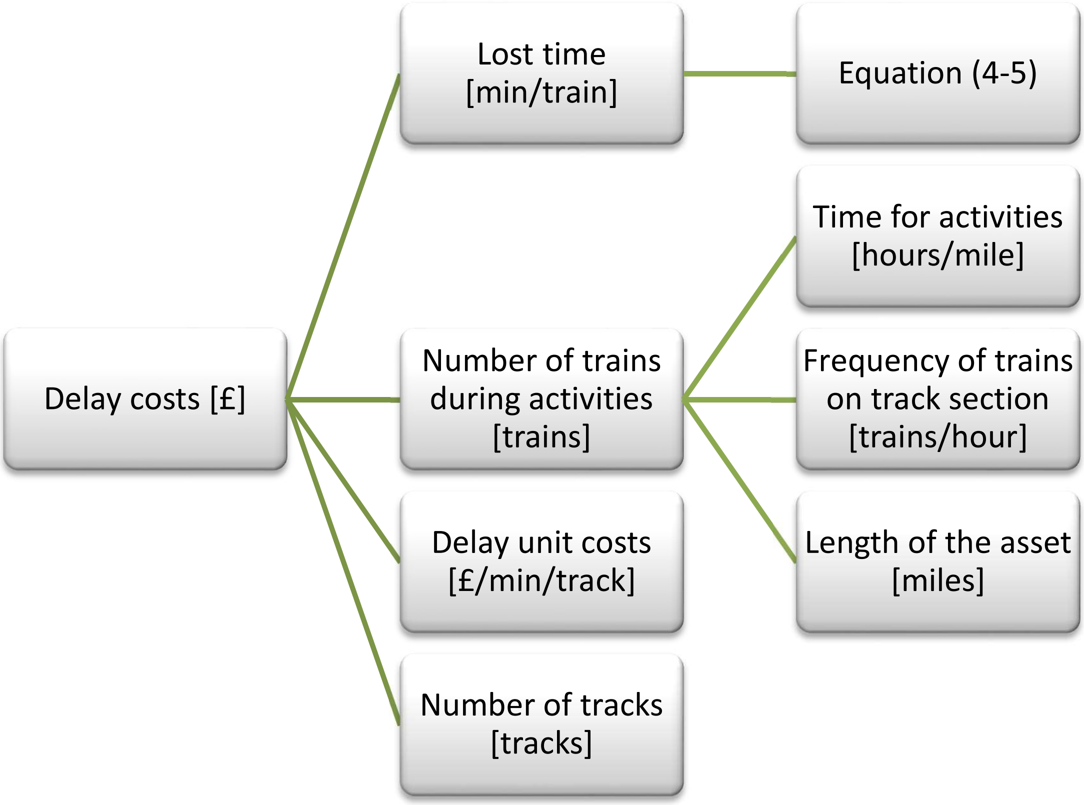

Figure 4-12 Delay costs breakdown

Lost time per train, (T_l, min/train), can be calculated as the difference in time taken to cross a portion of track (miles) run at restricted speed (S_r, miles/hour) as opposed to crossing the same section of track at normal speed (Sn, miles/hour)' (Reddy et al., 2007). The said portion of track depends upon the length of the restricted track (l_r, miles) and the average train length (l_t, miles):

$$T_l = [l_r + (3 * l_t)] * \left[\frac{60}{S_r} - \frac{60}{S_n}\right] \quad \textbf{(4-13)}$$

The length of the restricted track (l_r) varies according to the scenario considered: for track lowering and drainage works it equals the distance to be lowered while in the other two cases it is the length of the bridge. The analytical expressions are the equation (4-14)-(4-18)

$$Delay\ costs\ (initial\ track\ renewal)\ [£] \tag{4-14}$$
$$= Equation(4\text{-}13)\ \left[\frac{min}{train}\right]$$
$$* Average\ frequency\ of\ trains\ on\ the\ line\ \left[\frac{trains}{hour}\right]$$
$$* Time\ for\ single\ track\ renewal\ \left[\frac{hours}{mile}\right]$$
$$* Distance\ to\ be\ lowered\ [miles]$$
$$* Delay\ costs\ \left[\frac{£}{min * track}\right] * Number\ of\ tracks\ [tracks]$$

$$Delay\ costs\ (track\ renewal)\ [£] \tag{4-15}$$
$$= Equation(4\text{-}13)\ \left[\frac{min}{train}\right]$$
$$* Average\ frequency\ of\ trains\ on\ the\ line\ \left[\frac{trains}{hour}\right]$$
$$* Time\ for\ single\ track\ renewal\ \left[\frac{hours}{mile}\right]$$
$$* Length\ of\ the\ overbridge\ [miles]$$
$$* Delay\ costs\ \left[\frac{£}{min * track}\right] * Number\ of\ tracks\ [tracks]$$

$$\tag{4-16}$$

$$Delay\ costs\ (track\ lowering)\ [£]$$
$$= Equation(4\text{-}13)\ \left[\frac{min}{train}\right]$$
$$* Average\ frequency\ of\ trains\ on\ the\ line\ \left[\frac{trains}{hour}\right]$$
$$* Time\ for\ track\ lowering\ \left[\frac{hours}{mile}\right] * Distance\ to\ be\ lowered\ [miles]$$
$$* Delay\ costs\ \left[\frac{£}{min * track}\right] * Number\ of\ tracks\ [tracks]$$

$$\begin{aligned}
&\mathit{Delay\ costs\ (drainage)}\ [£] \qquad \textbf{(4-17)}\\
&= \mathit{Equation}(4\text{-}13)\ \left[\frac{min}{train}\right]\\
&* \mathit{Average\ frequency\ of\ trains\ on\ the\ line}\ \left[\frac{trains}{hour}\right]\\
&* \mathit{Time\ for\ drainage\ works}\ \left[\frac{hours}{mile}\right]\\
&* \mathit{Distance\ to\ be\ lowered}\ [miles]\\
&* \mathit{Delay\ costs}\ \left[\frac{£}{min * track}\right] * \mathit{Number\ of\ tracks}\ [tracks]
\end{aligned}$$

$$\begin{aligned}
&\mathit{Delay\ costs\ (OLE\ renewal)}\ [£] \qquad \textbf{(4-18)}\\
&= \mathit{Equation}(4\text{-}13)\ \left[\frac{min}{train}\right]\\
&* \mathit{Average\ frequency\ of\ trains\ on\ the\ line}\ \left[\frac{trains}{hour}\right]\\
&* \mathit{Time\ for\ OLE\ installation}\ \left[\frac{hours}{mile}\right]\\
&* \mathit{Length\ of\ the\ overbridge}\ [miles]\\
&* \mathit{Delay\ costs}\ \left[\frac{£}{min * track}\right] * \mathit{Number\ of\ tracks}\ [tracks]
\end{aligned}$$

4.6.5 Possession costs

Possession costs are supported when lines are closed to traffic to perform maintenance and repair activities. They are calculated similarly to delay costs, as Figure 4-13 shows.

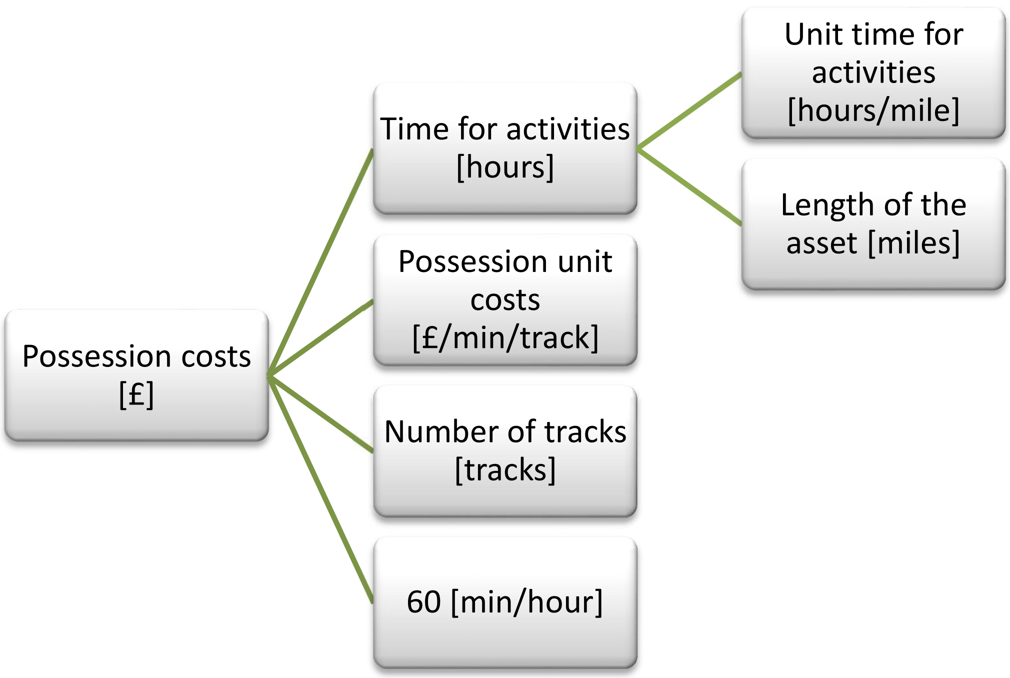

Figure 4-13 Possession costs breakdown

The analytical expressions are represented by equations from (4-19) to (4-24)

$$
\begin{aligned}
&Possession\ costs\ (track\ renewal)[£] \\
&\qquad = Length\ of\ the\ overbridge\ [miles] \\
&\qquad * Time\ for\ single\ track\ renewal\ \left[\frac{hour}{mile}\right] \\
&\qquad * Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right] \\
&\qquad * Number\ of\ tracks\ [tracks]
\end{aligned}
\tag{4-19}
$$

$$
\begin{aligned}
&Possession\ costs\ (bridge\ demolition\ and\ reconstruction)[£] \\
&= Time\ for\ bridge\ demolition\ and\ reconstruction\ [hours] \\
&* Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right] \\
&* Number\ of\ tracks\ [tracks]
\end{aligned}
\tag{4-20}
$$

$$
\begin{aligned}
&Possession\ costs\ (bridge\ renewal)[£] \\
&\qquad = \ Time\ for\ bridge\ renewal\ [hour\ \ ] \\
&\qquad * Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right] \\
&\qquad * Number\ of\ tracks\ [tracks]
\end{aligned}
\tag{4-21}
$$

$$Possession\ costs\ (OLE\ renewal)[£] \tag{4-22}$$
$$= Length\ of\ the\ overbridge\ [miles]$$
$$* Time\ fo\ \ \ OLE\ installation\ \left[\frac{hours}{mile}\right]$$
$$* Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right]$$
$$* Number\ of\ tracks\ [tracks]$$

$$Possession\ costs\ (track\ lowering)\ [£] \tag{4-23}$$
$$= Distance\ to\ be\ lowered\ [miles]$$
$$* Time\ for\ track\ lowering\ \left[\frac{hours}{mile}\right]$$
$$* Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right]$$
$$* Number\ of\ tracks\ [tracks]$$

$$Possession\ costs\ (drainage)\ [£] \tag{4-24}$$
$$= Distance\ to\ be\ lowered\ [miles]$$
$$* Time\ for\ drainage\ works\ \left[\frac{hours}{mile}\right]$$
$$* Possession\ costs\ \left[\frac{£}{min * track}\right] * 60\ \left[\frac{min}{hour}\right]$$
$$* Number\ of\ tracks\ [tracks]$$

4.7 Asset degradation models

The fourth step of the development methodology regards the estimation of assets condition for each year of the planning horizon, and the definition of the asset degradation models (Zoeteman, 2001). These in turn can be related to the expected traffic flow (MGT/year) with respect to tracks and potentially to overbridges and OLE as well; however, no analytical expressions were found in the literature regarding the last two assets.

4.7.1 Track degradation model

In order to find the behaviour of the asset, information are needed about:

- Expected annual traffic flow (MGT/year)

- Expected life of tracks (years) according to the traffic flow (MGT/year)

The former can be entered by the users, while the latter can be derived from Table 4-3.

Table 4-3 Economic life of a track (adapted from (Baumgartner, 2001))

	Gross traffic on one track (MGTK/year)			
	2.5-3.6	7.5-11	25-36	75-108
Life of track	40	22	11	6

Each value is, however, related to a restricted range of traffic flow, fact that makes the model still not applicable on all routes. Data are therefore turned into a continuous equation through interpolation techniques. In a similar way as to calculate overbridge maintenance costs, different interpolating equations are compared on the basis of the R^2 figure (Table 4-4).

Table 4-4 Equations for track degradation model

Baseline	Equation	R^2
Exponential	$y = 29.03e^{-0.01x}$	0.837
Linear	$y = -0.2946x + 29.626$	0.6244
Logarithmic	$y = -9.884\ln(x) + 47.554$	0.936
Polynomial	$y = -0.001x^3 + 0.1317x^2 - 4.4792x + 52.464$	1
Power	$y = 74.85x^{-0.559}$	0.999

In this case, two baselines present the same R^2 value. However, Figure 4-14 and Figure 4-15 show the power-like one better fits the data.

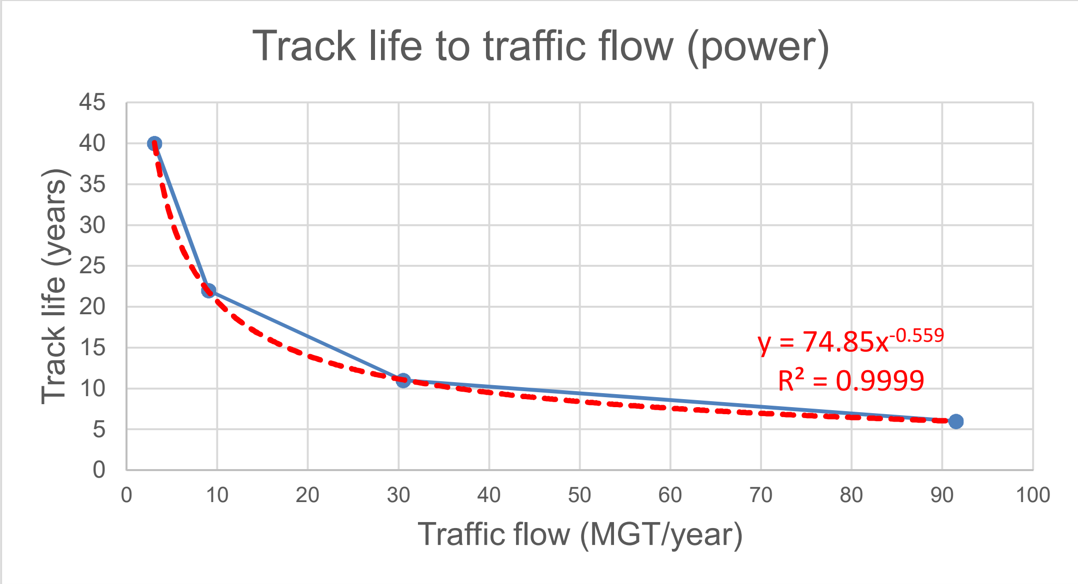

Figure 4-14 Snapshot of track life estimation with power interpolation

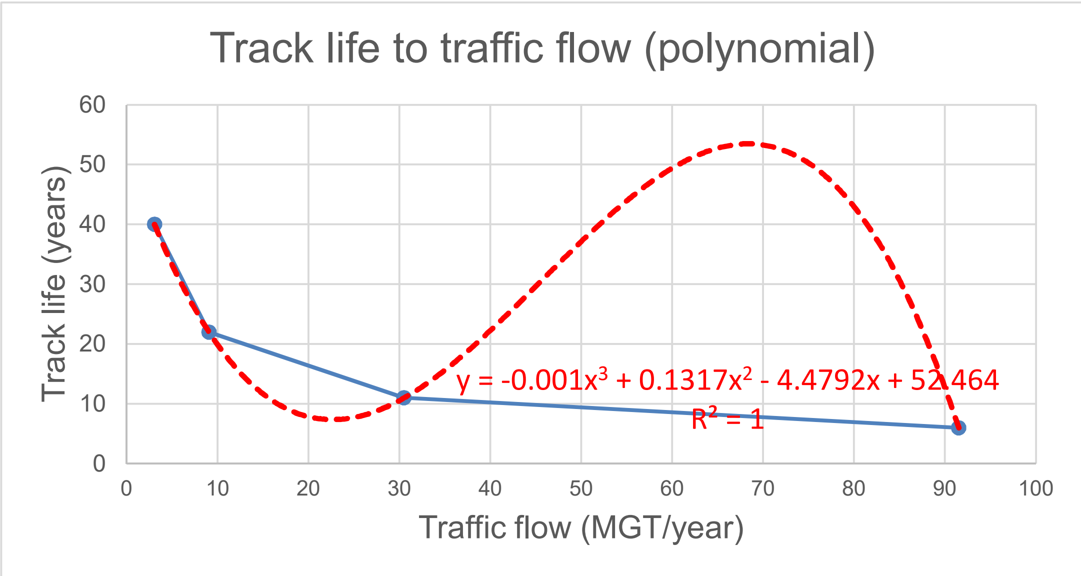

Figure 4-15 Snapshot of track life estimation with polynomial interpolation

The resulting equation, which models track life (years) in function of traffic flow (MGT/year), is the (4-25):

$$Track\ life\ (MGT) = 74.85x^{-0.559} \qquad \textbf{(4-25)}$$

According to the literature and Collaborator Company's practices, track behaviour depends on the 'quality' over the expected life (calculated using (4-25)). In particular, the quality (Q (t), %) over time (t, years) is related to the initial quality (Q_0, 100%) and to the degradation rate (b, dimensionless) with a negative exponential-like equation (section 2.7.1) :

$$Q(t) = Q_0 * e^{-bt} \quad \textbf{(4-26)}$$

The equation is still parametric since the degradation rate is not set. This parameter can be extracted by setting the equation (calculated in the expected track life value) equal to the user-defined quality threshold value for track renewals. For example, if practices prescribe the track must be replaced before its quality falls below 10%, this value is the one expected after applying equation (4-26) calculated in the expected life value, as written in equation (4-27).

$$Q(expected\ track\ life) = track\ renewal\ threshold\ (\%) \quad \textbf{(4-27)}$$

The tracks renewal threshold is to be set by model users.

4.7.2 Overbridge degradation model

Regarding overbridges, it was decided to use the equation found in the literature (2-2).

4.7.3 OLE degradation model

Given the limited asset modelling found in the literature, according also to industry current practices in asset management, the model uses the same pattern as for tracks (4-26), with expected life set in 15 years.

4.8 Summary

The steps for the development of the WLC cost model have been described in a structured and clear way, underlying the rationales behind the decisions taken. This chapter represents the basis for the following one, where the related software-tool is described.

5 TOOL DEVELOPMENT AND VALIDATION

5.1 Introduction

The present chapter constitutes the second core part of the research. In particular, it describes the development and validation of the software tool, which is considered the main outcome of the whole project.

The following sections explain how the tool embodies the features of the cost model and how it is possible to automate most of the calculations presented in the previous chapter. In the final part, mention is given to running trials and process followed for the validation of the tool and cost model as well.

5.2 Tool requirements

The requirements for the software-based tool have been in part outlined in the previous chapter. However, it is worth underlying the most important one is to present the outputs in a form that results easy to understand, and that shows with a histogram the relative magnitude of each group of costs. An additional line chart with non-discounted cash flows for each year of the planning horizon has been also designed. The purpose is to highlight the years in which major expenditures are expected in the future and enable user-companies to develop a well-balanced financial plan. An example of the cost profiles chart is provided in Figure 5-1.

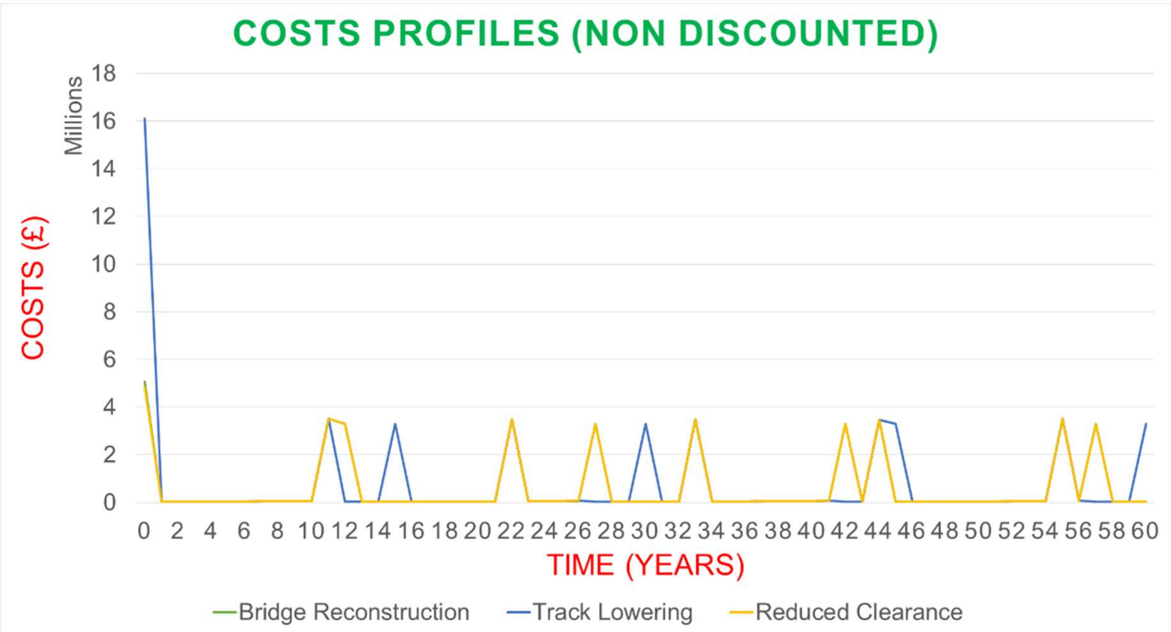

Figure 5-1 Snapshot of cost profiles chart

The cost model presented in the previous chapter depends upon several parameters, which in part can be considered fixed. However, the majority of them changes according to each business case, so that the tool is required to be parametric. As a general requirement, every software-tool needs also to be easy to navigate through and the presence of a flow chart can be therefore considered almost mandatory.

5.3 Tool structure

The tool has been developed within the MS Excel 2013 environment because of its intuitive graphic design and possibility to interface with other MS Office soft wares. It consists of eight spreadsheets with the first as an introductory screen, as shown in Figure 5-2.

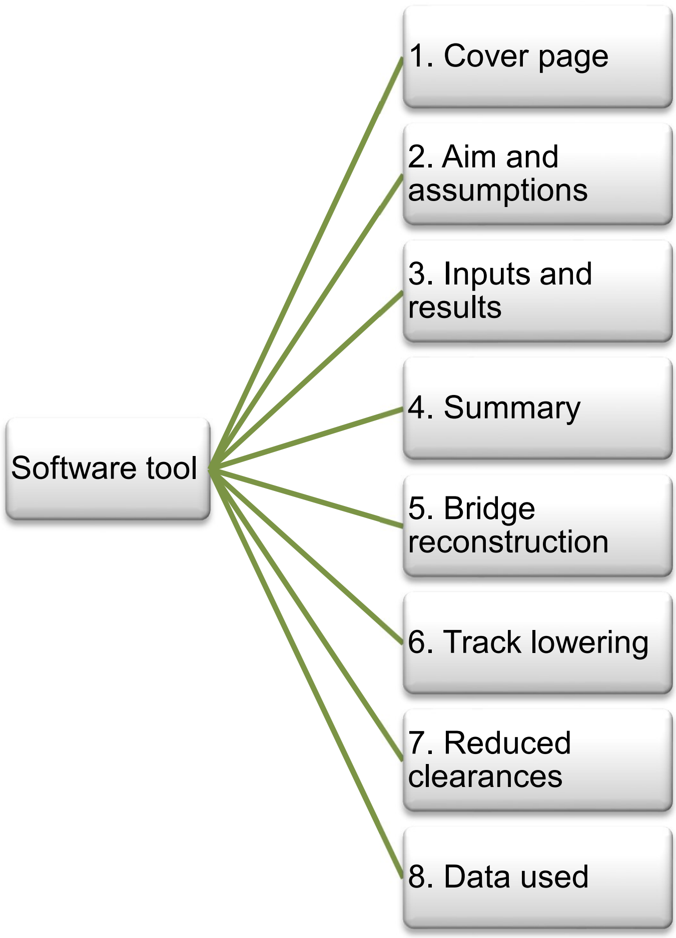

Figure 5-2 Software tool components

The second screen contains the tool navigation flowchart (Figure 5-3). As starting point, users are required to familiarise with the model through the reading of the assumptions and features listed below the flowchart. Then, the green-box hyperlink redirects directly to the '3.Inputs and results' screen, where it is possible to enter the parameters and have a first view of the results. The next step consists in checking and modifying, if needed, the data in ‘8. Data used’ screen; this is a compulsory phase because part of the data may vary according to each case. At this point, the user is redirected back to ‘3. Inputs and results’ screen to assess the results and take weighted decisions about the option to implement. Should the level of details be not sufficient, users can follow all or part of the following steps, which allow the visualization of the costs by year, by scenario and by asset, and finally check the results. In order to require minimal specific training to follow properly the logical steps, the tool is provided with green-written hyperlinks to move forward and backward to the flowchart screen.

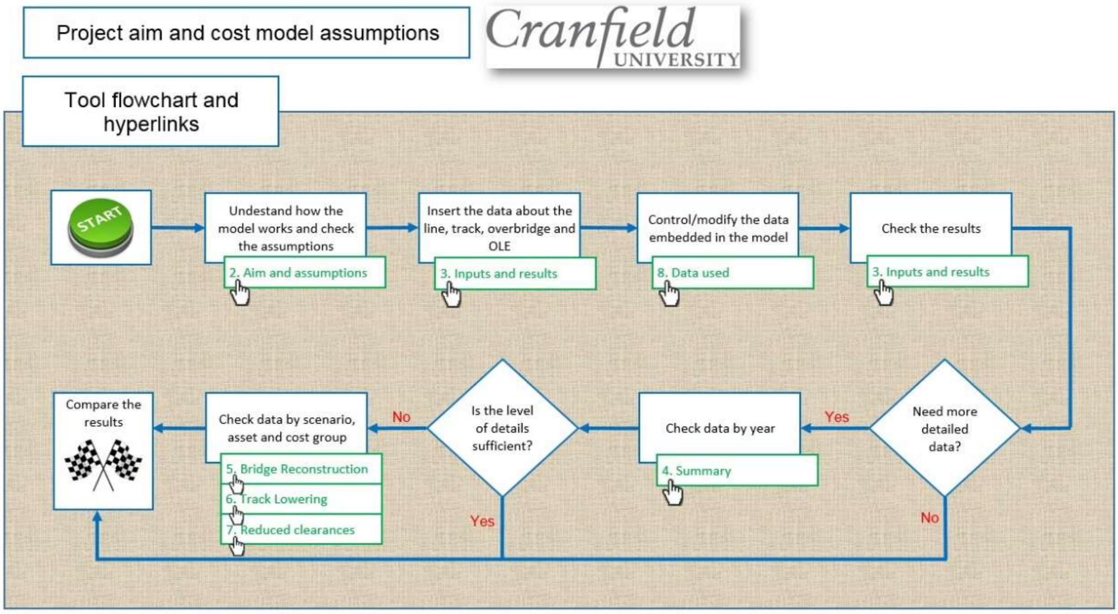

Figure 5-3 Tool flowchart

In the third screen, parameters are to be entered and results can be compared. The rationale behind the adjacency of results and input boxes is to enable visual and qualitative evaluations of the percentage by which the outputs result affected by changing inputs. In the following page, all costs from scenario spreadsheets are listed by year and used to create the output charts. Then, each scenario is assigned a spreadsheet, which contains the estimated costs first grouped by asset, then summed by year and finally discounted to initial ‘year 0’ using the NPV formula (4-1). In the last page, the additional data used by the model are presented: part of them, listed in Appendix E, are taken from the literature while the remaining figures (highlighted in red) are not fixed but need further investigations through additional databases. All mentioned parameters can be changed by model-users at own convenience and with no further actions, since calculations refer directly to the said cells when required.

5.4 The Developed Tool Outputs

The results are displayed in the third spreadsheet, '3. Input and results', close to the data entry boxes. Above the already mentioned costs profile spline chart, the histogram shows the costs for each single scenario summed up and split into CAPEX and maintenance costs. Figure 5-4 provides an example of the results, even if numbers should not be considered important because not related to real cases due to non-disclosure reasons.

Figure 5-4 Screenshot of histogram results

5.5 VBA code

The tool integrates in full the methodology followed for the cost model development. To increase the level of automation and decrease the number of steps for model-users to follow, equations discussed in sections 2.7 and 4.7 are added to the tool through the VBA code. Its simplicity of coding and check represents an additional valuable reason for considering MS Excel as a suitable tool development environment for this thesis. Detailed VBA codes are listed in Appendix A.

In particular, five VBA codes were created. The first four return the track condition for each year of the planning horizon according to the expected traffic flow, while the remaining one relates overbridge condition to its age (or time since construction). The logic flow of the track-related ones is presented in Figure 5-5.

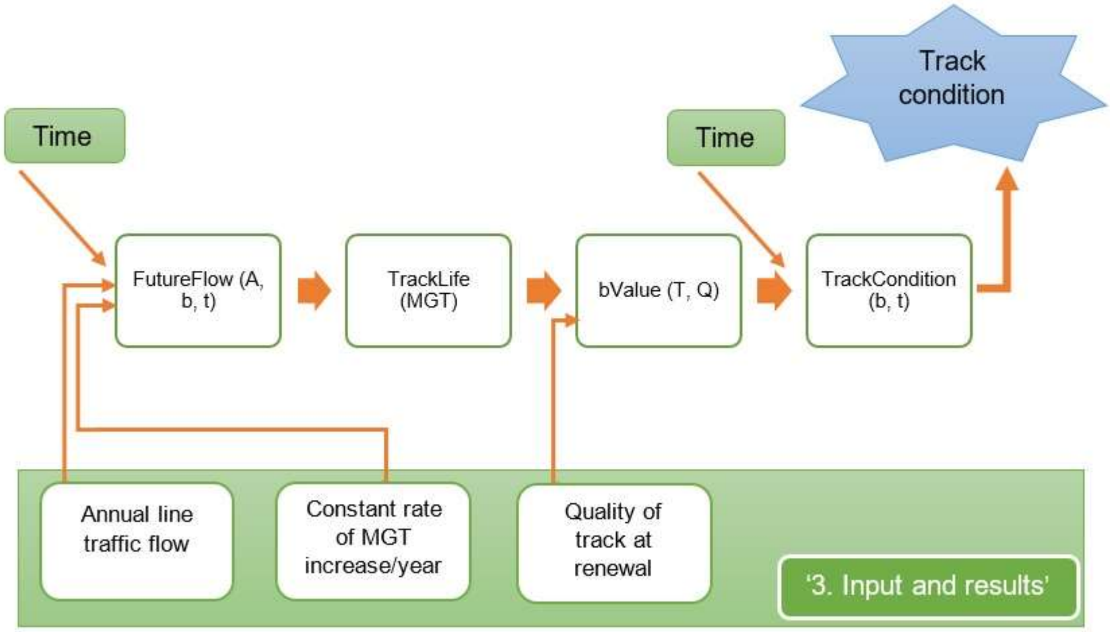

Figure 5-5 VBA code process

5.5.1 FutureFlow (A, b, t)

This function allows to estimate the traffic flow figure (MGT/year) all over the planning horizon. Since the industry has been experiencing increasing demand for transportation services for more than a decade (Network Rail, 2015a; Network Rail, 2013), increasing traffic flow should be reasonably considered. The hypothesis is that the rate will be constant over the whole 60 years. The function depends upon three variables:

1. A, initial traffic flow (MGT/year), set by model-users in the '3. Input and results page'
2. b, the increase rate per year (%), supposed constant overtime
3. t, the time (years)

The underpinning equation is therefore:

$$FutureFlow(A, b, t) = A * (1 + b * t/100) \quad \textbf{(5-1)}$$

5.5.2 TrackLife (MGT)

This function links the expected track life (T, years) to the forecasted traffic flow (MGT/year) calculated with FutureFlow. The equation coded is the (4-25).

5.5.3 bValue (T, Q)

At this stage, the track degradation model (4-26) is still not completely defined, since 'b' (degradation rate) has not been estimated yet. The bValue (T, Q) coded function depends upon two parameters:

1. T, the expected life of the track, calculated with TrackLife (MGT) (years)
2. Q, the quality of the track at track renewal (%)

In order to define 'b' along with the expected track life, the initial quality of the track (Q_0) is set at 100% and the equation (4-26) is then calculated for t equal to the expected track life. The returned value is the expected condition of the asset just before renewal operations and can be changed by model-users in the '8. Data used' spreadsheet. With all the parameters now defined, it is possible to estimate the value for 'b'. The equation used is then:

$$bValue(T, Q) = \left(\frac{1}{T}\right) * \log_e\left(\frac{100}{Q}\right) \quad \textbf{(5-2)}$$

5.5.4 TrackCondition (b, t)

Finally, track degradation model (4-26) is at this point defined and it is possible to calculate the condition of the asset (%). This function depends upon two variables:

1. b, the degradation rate, calculated with bValue (T, Q) (dimensionless)
2. T, time (years)

TrackCondition (b, t) is therefore the coded function for equation (4-26).

5.5.5 BridgeDegradation (t)

This function returns the condition of the overbridge (dimensionless) according to its age (t, years). The equation coded is the (2-2).

5.6 Sensitivity analysis

Sensitivity analysis is a process that investigates whether and how much the alternatives are sensitive to changing parameters, with the aim of highlighting the factors that have the greatest impacts on results and decisions (Bevilacqua and Braglia, 2000). Each relative influence is measured by varying one parameter at a time over a defined range. Though it represents the last step of the proposed cost model development methodology (Section 4.4), it has not been feasible to perform because it has not been possible to define some parameters within the project timescale, since their calculation would require the availability of specific different databases. The complete list of the parameters is provided in Table 5-1.

Table 5-1 Parameters to be evaluated

Name of parameters	Unit of measure
1. Reduced track life in track lowering scenario	years
2. Increase in track maintenance in reduced clear scenario	%
3. Increase in capital and renewal costs in reduced clear scenario	%
4. Increase in OLE maintenance hours in reduced clear scenario	%
5. Reduced OLE life span in reduced clearances scenario	years

In particular, these parameters should be considered not variable according to each case scenario and the sensitivity analysis would not be necessary. However, because their current unknown values, their influences on the results have been tested on two purpose-built case scenarios, where the said parameters have varied between 0% and 100% in case of percentage units of measure, and between 0 and 10 years for the remaining ones. The two case scenarios differ for the values of four additional parameters; in particular, if a parameter has a higher figure in the first case, then has a lower one in the second and vice versa, as shown in Table 5-2. Those parameters are the relevant ones to characterise each scenario, according to the case studies analysed in the Literature Review (Chapter 2).

Table 5-2 Running trials values

Parameter name	Unit of measure	Running trails	
		1	. 2
Traffic flow	MGT/year	25	10
Number of tracks	Tracks	2	4
Years from last track renewal	Years	9	2
Current age of the bridge	Years	10	80

The results of the analysis show all the parameters of Table 5-1 do not affect the decision when their value vary over the defined range. However, when the range is extended up to the value that determines a shift in decisions, parameters number 2 and 4 can bring modifications to the results with lower figures than the other three. Since calculations involve sensible data, the exact values are not provided within the text for non-disclosure reasons.

5.7 Running trials and validation

This section describes the process that was followed to validate the WLC cost model after its development. Throughout the duration of the project, several meetings with the AUTONOM Project Cost Analysis team were held at Cranfield University to define requirements and desired outputs of the model and tool as well (Phase 5).

As a common last step of any model development, it is worth testing the results on real case studies to verify and validate the research methodology followed and the estimations made. However, not always this can be feasible and the analysis can shift from a translation of behaviours and patterns into numbers for statistical analysis (quantitative research) rather to an understanding of behaviours and patterns, leading to the development of potential for quantitative research (qualitative research). In the case of this thesis, due to hazier contacts with the Collaborator Company towards the end of the project, the validation phase assumes the characteristics of the qualitative research.

5.7.1 Running trials

The tool has been applied to two running trials (whose value are the same as of Table 5-2) in order to verify some findings from the literature and suppositions expressed during technical meetings with the stakeholders. The results, shown in Figure 5-6, are in accordance with the fact that the third option is characterised by lower WLC total costs and, specifically, small CAPEX figures, while maintenance levels are higher than in the other two scenarios. It is confirmed that track lowering is the most expensive option in both cases, for the major part due to high CAPEX and service disruption costs. With specific references to these two trials, the higher number of tracks in the second scenario implies, in addition, an increase in costs almost proportional for CAPEX and more than proportional for maintenance activities. These findings do not belie the provisional decision of the railway industry to consider no more track lowering option for future electrification projects. The overall conclusion is that the two running trials give one possible explanation of the reason why the industry, during the development of the project, has gradually moved the interest in favour of the third scenario. Detailed description of the value used for other non-mentioned parameters can be found in Appendix B.

Figure 5-6 Running tests results

5.7.2 Validation

The final approval has been obtained through three different validation sessions with in total six representatives of the AUTONOM Project. The choice of the validation group members has stemmed from their close contacts with the Collaborator Company and complete knowledge of aim and objectives of the AUTONOM project as well. Each session has consisted in a presentation of the project, cost model and tool, followed by a six-question questionnaire. The team has been asked to provide a rank between 0 and 5 on questions like:

- “Is the model intuitive to use?”
- “Are the results easy to compare?”
- “Is the model coherent with the AUTONOM Project practices?”

The complete questionnaire is provided in Appendix C.

The model has been considered in line with the AUTONOM project aim and objectives (with an average of 4.5 out of 5) and the results have been found easy to compare. Regarding the easiness of navigation, during the first two sessions the assessors have suggested possible improvements for the graphic and have noticed the lack of a tool process flow. Those two considerations have triggered modifications that finally have encountered positive response during the last validation session. The level of details has been considered appropriate (scored 4.17 on average) and the tool aligned with the project aims and objectives.

The three validation sessions have globally highlighted other areas of improvements. In particular, it has been pointed out that the tool may provide different answers based on the assumptions set and that the evaluations should include the denial of service costs group, which depend in turn upon assets failure rates and modes. Finally, getting ideas also from the Literature Review (section 2.9), it has been considered of interest that the tool would model as well costs for a fourth option characterised by ‘neutral sections’.

5.8 Summary

The structure and features of the Excel tool have been described within the present chapter, with particular references to the decisions made to adapt it to the cost model and to the requirements of project stakeholders. The validation process has been presented as well, through the description of the trials run and the opinions of academic experts, collected with a proposed questionnaire.

6 DISCUSSION

6.1 Introduction

The presented work aims at developing two results. The first is a model that helps decision-makers to evaluate the available infrastructure options to extend the OLE to overbridges. The second is a software tool that enables the automation of the decision-making process and returns the results in a format that enables easy and swift comparisons.

6.2 Research methodology discussion

The research methodology results aligned with the aim and objectives of the thesis. Through its phases, in fact, it is possible to consider not only the findings from the literature but also the current practices within the industry, in order to eventually give consistency to the results obtained.

The very first activities regarded the understanding of the project through meetings with the stakeholders; this phase resulted of utmost importance to define aims, objectives and scope to guide the whole development within the limited timescale. A project plan was also provided in the Client Research Brief with the purpose of setting the principal milestones and deliverables over the four months and check whether the thesis resulted on time or delayed.

Given the high number of information needed for a WLC cost model developments, the methodology includes an extended Literature Review, through the analysis of not only academic papers but also of more up-to-date industry companies' official websites. It has been useful to understand and present the reasons why WLC is considered the best option to take decisions, especially during the first phases of the lifecycle and also when the planning horizon spans over several decades, such as the case of the present thesis.

The model was developed according to the main findings of both the literature and current practices within the industry, in order to maximise its practical usability. The methodology development, in fact, resulted in a combination of one proposed by researchers and the one used by the major player in the railway sector. Infrastructure options were described from a technical point of view, with a particular focus on the implications on asset behaviours and WLC costs. The tool was developed only after the completion of the cost model, and includes not only all the calculations through the VBA programming code but also all the steps of the decision-making process, through the provision of the built-in flow chart.

Finally, the methodology provides for results validation, in order to check upon the achievement of the thesis aim. However, a standard validation through application to a real case study has been left to future works because of time reasons. Finally, planned backtracks among the last phases enabled to incorporate feedbacks and suggestions made by the project stakeholders.

6.3 Research Results discussion

6.3.1 Cost model

The Whole Life Cycle cost model successfully meets the aim of the project. First of all, its development methodology is consistent with the findings of the literature and current practices within the company as well. In addition, the model complies with the requirements set by the ORR.

Costs are estimated for the three major asset affected by infrastructure alterations (tracks, overbridges and OLE), since every option has specific implications on CAPEX and maintenance costs regarding all the said assets. This observation results aligned with the literature, which treats the challenge of electrical clearances as multi-asset projects that require considerations beyond the sole electrification system. Estimations include also delay and possession costs, which the industry is very sensitive to (Section 2.5); their ignorance could lead not only to non-optimal solutions but also to worse partnerships between TOC and infrastructure managing companies, as bigger figures would turn into greater delays and train cancellations.

The cost model development methodology has a strong focus on asset degradation and condition as main cost drivers of maintenance costs. This is true especially for tracks, where a set of analytical steps allow to return the condition of the asset along with the traffic on the line, as suggested by the literature. This decision would make the model usable and further developable by the AUTONOM Project researcher, as well as giving general guidelines for railway costs modelling.

Finally, due to the 60-year planning horizon, an outlook of the industry is also discussed and included within the development steps, especially with regards to the increase in traffic flow and changes in climate patterns.

6.3.2 Software tool

The software tool as well results properly developed, according to the needs of industry decision makers. The flow chart guides the users to navigate through the spreadsheets and helps them to follow the underlying methodology step by step. Main results are displayed with a histogram where each bar corresponds to one option and the division between CAPEX and maintenance costs is highlighted by different colours. This last point results of particular interest from the users point of view as final decisions may not necessarily look only for total costs minimisation but also for the option with the lowest maintenance costs, due to the expected future restrictions of track possession times. An additional spline chart with cost profiles for each option over the whole planning horizon is also provided, with the purpose of highlighting the occurrence times of major expenditures and allow therefore user-companies to develop a balanced financial plan. The insertion of the equations through the Excel VBA code allows for a good level of automation and overall low level of complexity.

The structure of the tool enables future users to further consider additional groups of costs, such as safety risk costs, but also additional options, such as ‘neutral sections’. Especially in the last case, the related spreadsheet could be easily derived from the reduced clearances one and updated with additional findings from the research. Finally, during one of the validation sessions, it has been noticed that the tool could be integrated through little modifications with condition-based maintenance strategies; this could happen by designing a new field to import figures coming from the sensors installed on the network and by referring to them all the following costs cells.

6.4 Research limitations

The initial idea of the project was to derive an OLE degradation model from the data provided, and calculate a difference in OLE maintenance levels for each scenario. This would make the model more related to the data provided, but not always prompt contacts with the Collaborator Company and, first of all, the lack of an overbridge asset register made the path harder to follow. In particular, the register would make the model suitable also for tunnels, which, conversely than overbridges, differ markedly among themselves for their length. Higher level of maintenance could not necessarily be related to one particular infrastructure option but simply to the higher number of components they consist of.

Due to the limited time available for project development, the greatest limitation of the research is the non-consideration of uncertainties for parameters. The industry deals continuously with non-deterministic parameters and many software are developed to take into consideration statistical distributions and risks associated to statistical variances from means. That would lead to Monte Carlo simulation, which is considered as almost mandatory for any railway cost tool.

Finally, owing to the lack of data regarding tracks and overbridges, five parameters are at the moment not defined in value and this prevent from performing a complete sensitivity analysis. However, trial simulations made by the author have suggested that parameters influences would not affect substantially total costs or change the conclusions within a reasonable limit.

7 CONCLUSIONS AND FURTHER WORKS

7.1 Introduction

This last chapter aims at summarising the main outcomes of the project, with an analysis of the principal conclusions and contributions brought to knowledge. Suggestions for further works are also made to improve the tool and enrich it with additional features.

7.2 Contribution to knowledge

From the discussion of the available Literature has emerged a substantial lack of structured methodologies to face the challenge of electrical clearances. In particular, the gap is related to the absence of multi-asset cost methodologies that look over the simple installation phase, but rather consider also the consequences of the options on future maintenance activities.

This work has provided a Whole Life Cycle cost model that accounts for the behaviour of the main assets involved in infrastructure modifications (tracks, overbridges and OLE) over a 60-years planning horizon. It includes capital expenditures and maintenance costs, with related possession and delay costs when the activities are performed. The model has been designed to assess the three described options but it is suitable for extensions to other asset configurations for infrastructure alterations or other group of costs.

The project aim has led also to the creation of a software tool that enables for more efficient and effective decision-making processes. This has been achieved through a built-in flowchart, which guides the users throughout the process, and with the visualization of the total costs by means of a histogram, where each option is represented by a bar. The tool has been developed as a parametric on the parameters that vary according to each business case, so that the model can be serviceable on any case on any route. Finally, the model can be extended with reasonable easiness to consider additional cost groups, infrastructure options (such as ‘neutral sections) or even asset conditions coming from the condition-based monitoring systems.

7.3 Conclusions

The research of the best solution to comply with electrical clearances standards under overbridges, is a challenge the railway industry has been facing during current and past electrification projects and it is expected to recur also in the future. Since railway projects generally involve considerable total expenditures, their profitability would substantially increase just with small percentages of costs reductions during each year of the planning horizon.

For these reasons, a Whole Life Cycle cost model has been developed to consider the options not only for their implications on civil works alterations but also on maintenance and renewal operations. It is the result of the integration of the relevant findings from the Literature and of current practices within the railway industry. Finally, it accounts for the behaviour of the major assets involved in modifications and calculates the costs on the basis of the assets conditions. A software-based tool was also developed to automate the calculations and improve the decision making-process through an effective display of the total costs with histogram bars.

The overall results of the research were validated through opinions of experts from Cranfield University, who appreciated the user-friendliness of the tool and its suitability for further integrations with condition-based maintenance strategies

7.4 Future research

In order to provide structured guidelines for further works, future activities would:

1. Extend estimations to service risks costs and ‘neutral sections’ scenario
2. Include uncertainties associated with parameters and probability distributions, followed by Monte Carlo simulation runs
3. Integrate condition-based maintenance strategies by adding fields and hyperlinks to data coming from sensors across the network
4. Define the parameters of Table 5-1 through additional databases
5. Consider end of life costs

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APPENDICES

Appendix A VBA code

A.1 FutureFlow (A, b, t)

```
Cost model 2.2.2.xlsm - MGT (Code)
(General)    FutureFlow

Function FutureFlow(A, b, t)
'A is the initial traffic flow
'B is the percentage of increment
't is the time in years
FutureFlow = A * (1 + b * t / 100)
End Function
```

Figure A-1 VBA code for FutureFlow (A, b, t)

A.2 TrackLife (MGT)

```
Cost model 2.2.2.xlsm - Life_of_the_track (Code)
(General)    TrackLife

Function TrackLife(MGT)
'MGT is the expected value of traffic flow
TrackLife = 74.85 * MGT ^ (-0.559)
End Function
```

Figure A-2 VBA code for TrackLife (MGT)

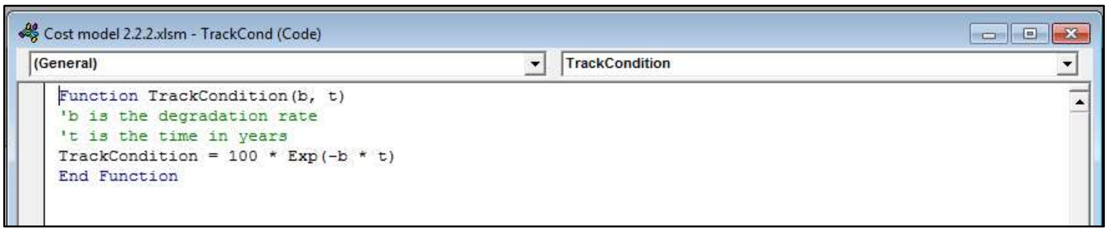
A.3 bValue (T, Q)

```
Cost model 2.2.2.xlsm - Calculation_of_b (Code)
(General)    bValue

Function bValue(t, Q)
'b is the degradation rate, which is a function of time and traffic flow, but supposed constant
't is the expected life of the track
'Q is the quality at the moment of track renewal
bValue = (1 / t) * Log(100 / Q)
End Function
```

Figure A-3 VBA code for bValue (T, Q)

A.4 TrackCondition (b, t)



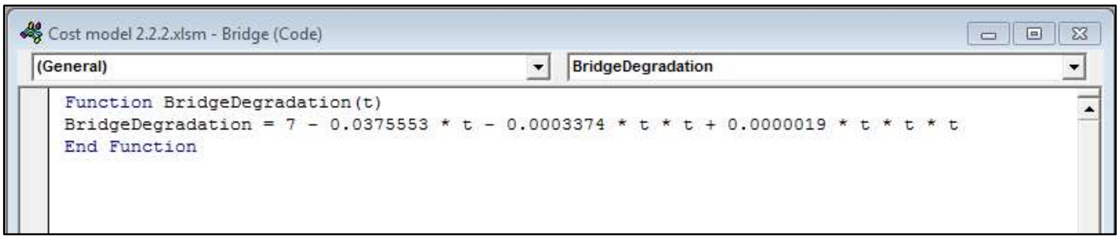
Cost model 2.2.2.xlsm - TrackCond (Code)

(General) | TrackCondition

```
Function TrackCondition(b, t)
'b is the degradation rate
't is the time in years
TrackCondition = 100 * Exp(-b * t)
End Function
```

Figure A-4 VBA code for TrackCondition (b, t)

A.5 BridgeDegradation (t)



Cost model 2.2.2.xlsm - Bridge (Code)

(General) | BridgeDegradation

```
Function BridgeDegradation(t)
BridgeDegradation = 7 - 0.0375553 * t - 0.0003374 * t * t + 0.0000019 * t * t * t
End Function
```

Figure A-5 VBA code for BridgeDegradation (t)

Appendix B Running trials data

Table B-1 Non-changing parameters in running trials

Parameter name	Value	Unit of measure
Constant rate of MGT increase per year	0.05	%
Possession costs	50	£/min/track
Normal speed of the track section	125	Miles/hour
Restricted speed	30	Miles/hour
Delay costs	50	£/min/track
Average frequency of trains on section	20	Trains/hour
Distance to be lowered	0.6	Miles/hour
Renewal threshold for tracks	20	%
Annual track maintenance (when new)	3,000	£/year/track
Time for single track renewal	30	Hours/mile
Time for track lowering	100	Hours/mile
Time for drainage works	50	Hours/mile/section
Time for bridge renewal	100	Hours
Bridge renewal costs	650,000	£
Length of the overbridge	0.05	Miles
Time for bridge demolition and reconstruction	80	Hours
Renewal threshold for OLE	20	%
OLE maintenance executors wage	50	£/hour
Time for OLE installation	50	Hours/mile
Condition of the track at renewal	10	%
Reduced track life in track lowering scenario	5	Years
Increased track maintenance in reduced clearances scenario	30	%

Increase capital and renewal costs in reduced clearances scenario	30	%
Increase in maintenance hours in reduced clearances scenario	10	%
Reduced OLE life span in reduced clearances scenario	5	years

Appendix C Validation questionnaire

MSc Thesis September 2015

'Analysis of infrastructure options and the cost implications in the railway industry'

Project aim: To develop a Whole Life Cycle Cost Model to assess the best infrastructure option to extend the electrification to overbridges

Cost Model Tool Validation Questionnaire

The purpose of the present document is to collect experts' opinions and suggestions for the improvement and validation of the cost model

Student: Lorenzo Giuntini

Supervisors: Dr. Essam Shehab, Dr. Leigh Kirkwood, Dr. Paul Baguley

_______ Cost Model Tool Validation Questionnaire ______

Name:
Area of expertise:
Number of years of experience in own area:

INSTRUCTIONS

1. Circle the appropriate number according to the table below:

1	2	3	4	5
Definitely not satisfied	Not satisfied	Uncertain	Satisfied	Completely satisfied

QUESTIONS:

1. Is the model intuitive/easy to use? 1 2 3 4 5

Comments

2. Are the results easy to compare? 1 2 3 4 5

Comments

3. Is the tool fit for the purpose? 1 2 3 4 5

Comments

4. Is it graphically easy to read? 1 2 3 4 5

Comments

5. Is there the right level of details? 1 2 3 4 5

Comments

6. Is the model coherent with the Autonom Project practices? 1 2 3 4 5

Comments

Please, provide any additional comment.

Thank you,

LORENZO GIUNTINI

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Appendix D Cost model assumptions

1. Capital costs are supported only during initial ‘year 0’
2. The discount rate is constant over the planning horizon
3. Renewal activities are performed once the asset condition falls below the renewal threshold level (multi-asset renewals were not considered)
4. OLE installation is performed during major engineering works so that possession costs and delay costs were not considered, except for reduced clearances scenario
5. Preventative and corrective maintenance costs are merged into a single value
6. Before performing renewal activities, asset age counter is set automatically at 0 and engineering or renewals activities last for the whole ‘year 0’
7. No carrying highways or services were considered in the analysis
8. Parameters are supposed deterministic
9. Track renewals are done separately on each track, while the other ones remain in service but with speed limits
10. During bridge demolition and reconstruction only possession costs will be supported
11. The three options are mutually exclusive

Appendix E Data used and sources

Activity name	Value	Unit of measure	Font
Bridge demolition and reconstruction	Confidential	£	Meetings with industry companies
Bridge maintenance costs when new	950	£	Section 4.6.2
Bridge average life span	120	years	(Du and Karoumi, 2013)
Rail renewal unit costs	75,000	€/m/track	(Caetano and Teixeira, 2014)
Track lower ballast permanent way works unit costs	574	£/m/track	(Rail Safety & Standards Board, 2007)
Drainage works unit costs	354	£/m/route	(Rail Safety & Standards Board, 2007)
Electrification unit costs	575,000	£/mile/track	(Rail Safety & Standards Board, 2007)
OLE life span	15	Years	(Shing and Wong, 2008)
Removal of along track equipment unit costs	20	£/m/track	(Rail Safety & Standards Board, 2007)
Installation of new along track equipment unit costs	60	£/m/track	(Rail Safety & Standards Board, 2007)